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RESEARCH MEMORANDUM

STARTING AND PERFORMANCE CHARACTERISTICS OF A LARGE ASYMMETRIC SUPERSONIC FREE-JET FACILITY

By Ferris L. Seashore and Herbert G. Hurrell

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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STARTING AND PERFORMANCE CHARACTERISTICS OF A LARGE ASYMMETRIC SUPERSONIC FREE-JET FACILITY

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SUMMARY

An asymmetric free-jet facility, for which the design Mach number was 2.755, was constructed for the investigation of a 48-inch-diameter ram-jet engine and the associated asymmetric supersonic inlet and inlet diffuser. Prior to beginning the ram-jet investigation, the starting and performance characteristics of the free-jet facility were evaluated. The following range of conditions covered the facility performance investigation: supersonic nozzle-inlet total pressures from 1616 to 2900 pounds per square foot absolute, corresponding to air flows of 100 to 180 pounds per second, respectively, and supersonic nozzle-inlet temperatures from 425° to 545° F. The conditions for the starting investigation covered a higher range of inlet-air pressures and humidities and lower inlet-air temperatures.

The design flow could not be established in the Mach 2.755 asymmetric nozzle with dry air at the design temperature of 528° F even though an over-all pressure ratio of 11 was used. It was found that by using low-temperature air with high moisture content it was possible to attain the design flow with an over-all pressure ratio as low as 5; however, it was necessary to operate the facility at a pressure ratio of about 6 when dry air at the design temperature of 528° F was used.

The facility performance investigation showed the free-jet flow to be sufficiently uniform in velocity and flow angle to satisfactorily simulate the internal flow of the supersonic inlet, the inlet diffuser, and the 48-inch ram-jet engine. The average weighted Mach number of the inlet capture area was 2.765. The Mach number varied from -0.3 to 2.7 percent of the design Mach number of 2.755. The maximum angle of flow deviation was ±1.7°.

INTRODUCTION

The performance of ram-jet engines at high Mach numbers may be obtained from flight, supersonic wind-tunnel, direct-connect, and free-jet

testing. Flight testing, of course, gives exact simulation of both internal and external flows; but this type of investigation is not always adequate because of instrumentation difficulties, short testing time, and the risk of engine loss. The supersonic wind tunnel provides excellent simulation of internal and external flows, but the cost would be great for a high Mach number wind tunnel which could accomodate large engines. The direct-connect method of testing, in which air is piped directly to the engine at pressures and temperatures corresponding to flight operation and thus provides a partial simulation of the internal flow, is relatively inexpensive, convenient, and useful for some types 3205 of combustor tests; but this type of testing may not give the right flow distribution at the combustor inlet if operation in conjunction with a given diffuser is desired. The free-jet method of testing provides good simulation of internal-flow conditions at a fraction of the cost of a supersonic wind tunnel and is satisfactory if it is not necessary to simulate external flow or (in most cases) subcritical flow. Therefore, information on the starting and performance characteristics of free-jet facilities is of interest to those engaged in the development of ram-jet engines.

In the free-jet facility, in order that flow conditions be properly simulated at the supersonic inlet of the ram jet, it is necessary that the air flow through the supersonic nozzle be greater than that required by the engine; thus the air-flow requirements are high for large engines. In addition, high pressure ratios are required to establish the supersonic jet. In order to permit operation over a maximum range of simulated flight conditions within the air-flow and pressure-ratio limitations of given air-handling equipment, therefore, the design of the facility itself must be aerodynamically correct and properly matched to the engine and its flow requirements.

Several previous investigations of the design and performance of free-jet facilities have been reported. Investigations of the design of jet diffusers, the optimum free-jet nozzle size, and the positioning of the inlet with respect to the nozzle are reported in references 1 and 2. The special problems associated with asymmetric free-jet facilities are considered in reference 2. An investigation of a free-jet facility large enough for a 20-inch ram-jet engine is reported in reference 3.

The starting and performance characteristics of a large asymmetric free-jet facility, with a design Mach number of 2.755, installed in an altitude chamber of the NACA Lewis laboratory is the subject of this report. The facility was constructed to permit simulation of internal-flow conditions for an investigation of a 48-inch-diameter ram-jet engine and the associated asymmetric side inlet and diffuser at zero angle of attack. An asymmetric facility was used in order to permit proper simulation of flow conditions at the side inlet with the smallest

possible supersonic free-jet nozzle and thus with the minimum air-flow requirement. The facility permits simulation of altitudes from about 60,000 to 81,000 feet as limited by the air-handling equipment.

A special technique required to establish the design flow in the facility is reported, and the over-all pressure-ratio requirements of the facility and the performance of the supersonic nozzle and jet diffuser are presented.

SYMBOLS

The following symbols are used in this report:

M Mach number

P total pressure, lb/sq ft abs

p static pressure, lb/sq ft abs

T total temperature, ^{o}F

β Mach angle

γ ratio of specific heats

θ stream flow angle

Subscripts:

a facility exhaust chamber

b boundary layer

c jet chamber

i supersonic inlet plane (lip)

j supersonic-nozzle discharge plane

n supersonic-nozzle inlet

0 free stream

1 behind a normal shock

DESCRIPTION OF FACILITY

General

The free-jet facility was constructed by installing a supersonic nozzle and a jet diffuser in the 14-foot-diameter section of an altitude chamber. A cutaway drawing showing the installation complete with supersonic nozzle, jet diffuser, inlet diffuser, and the 48-inch-diameter ram-jet engine is presented in figure 1. Plan and elevation views of the installation are shown in figure 2.

Air at the stagnation conditions corresponding to altitudes above the tropopause and a flight Mach number of 2.76 was supplied to the nozzle inlet by the laboratory air system. Air driers in the compressed-air system lowered the moisture content of the air sufficiently to avoid condensation shocks in the supersonic nozzle. The air was heated to the proper nozzle-inlet temperature by means of gas-fired heat exchangers. The use of heat exchangers permitted heating of the air without the contamination common to direct-combustion preheaters. The air flow leaving the test chamber was handled by the laboratory exhauster equipment. A water-spray apparatus was installed in the inlet-air duct (downstream of the heaters) for use in the starting investigation involving moist inlet air.

Supersonic Nozzle

A supersonic nozzle of semicircular cross section with an exit diameter of 66 inches was used in the facility. The design Mach number was 2.755. The size and shape of the nozzle resulted from the following considerations:

(1) The nozzle was to be used in conjunction with a particular supersonic side inlet which was approximately semicircular in cross section.

(2) Boundary-layer air from the supersonic nozzle should not enter the inlet.

(3) The air-flow requirement of the facility should be a minimum so that a maximum range of altitudes could be simulated.

(4) A ratio of supersonic-nozzle exit area to inlet capture area of 2.15 was indicated to be satisfactory (according to the results of ref. 2) to keep the facility pressure-ratio requirements within the pressure-ratio limitations of the air-handling equipment.

The nozzle, exclusive of the boundary-layer adjustment, was designed by North American Aviation, Inc., with the aid of the method of characteristics for the supersonic portion. Adjustment of the nozzle coordinates for boundary-layer growth was made at the NACA Lewis laboratory by using the method of reference 4 in the same manner as described in reference 3. Final smoothing of the adjusted coordinates by the method of item differences (ref. 5) completed the nozzle design. The final coordinates including the boundary-layer adjustment are given in table I.

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The completed nozzle, which was furnished by the U.S. Air Force, was about 20 feet long and weighed 20,000 pounds. The nozzle was fabricated in six sections; five semicircular sections were machined from Meehanite castings and the sixth, a bellmouth section, was constructed of 1/8-inch sheet steel. The "floor" of the machined portion was made in two pieces from 1-inch sheet steel.

Jet Diffuser

The jet-diffuser design was based on information obtained from the small-scale tests of reference 3. The faired inlet diffuser served as the inner contour. The outer contour of the convergent-divergent jet diffuser was approximately semicircular in cross section and was fabricated from sections of sheet steel. The throat of the jet diffuser was sized to give a ratio of jet-diffuser throat area to supersonic-nozzle discharage area minus the inlet capture area of 1.27. The jet diffuser was designed so that the ram-jet engine was accessible. A section, which is referred to as the jet chamber, was placed between the supersonic nozzle and the beginning of the jet diffuser in order to provide for a shadowgraph installation. This section was made large enough in diameter to permit increasing the jet-diffuser throat area if needed.

The inlet-diffuser mounting supports required fairing to avoid excessive pressure losses in the jet diffuser. The inlet diffuser was supported from underneath by two I-beams running almost its entire length. The supports at the upstream end were enclosed in a wedge-shaped fairing to minimize pressure losses. The air flow entering the inlet was shielded from disturbances from this wedge by the boundary-layer scoop plate of the supersonic inlet. The floor-wedge installation can be seen in figure 1.

INSTRUMENTATION

Pressure instrumentation was installed at two locations near the supersonic-nozzle exit to survey the flow field. Rakes were installed from the floor immediately upstream of the inlet spike and from the circular portion of the nozzle a short distance ahead of the nozzle exit.

The rakes at these two stations were in place at different times. Pitot-tube rakes were used to determine the Mach number distribution. Wedge-type rakes were also used for an independent check on Mach number and for determining the flow angle. In addition to these rakes, a boundary-layer pitot-tube rake was installed at both survey stations in the supersonic nozzle. The position and details of the rakes are shown in figure 3.

Other facility pressure instrumentation included:

(1) Three pitot-tube rakes at the supersonic-nozzle inlet

(2) Wall static-pressure orifices in the supersonic nozzle

(a) The wall orifices were distributed longitudinally along the top of the nozzle.

(b) Circumferential distribution of the wall orifices was made at the throat and near the exit.

(3) Five wall static taps in the jet chamber distributed circumferentially outside the jet

(4) Wall static taps distributed longitudinally along the outer contour of the jet diffuser

(5) One wall static tap in the facility exhaust chamber

(6) A pitot-tube rake in the engine combustion chamber at the exhaust-nozzle inlet

The pressures were indicated on manometers with fluids providing a reading accuracy of about 1 percent and were recorded simultaneously by photography. The total temperature of the air was measured with thermocouples mounted on the pressure rakes located at the entrance to the supersonic free-jet nozzle.

Shadowgraph observation of flow conditions at the supersonic inlet was made through photographic recordings and direct viewing from the control room.

PROCEDURE

Calculation

Mach number values determined from the pitot-tube rakes were obtained from the expression

$$\frac{p_1}{p_n} = \left[\frac{(\gamma + 1)M_0^2}{(\gamma - 1)M_0^2 + 2}\right]^{\frac{\gamma}{\gamma-1}} \left[\frac{2\gamma M_0^2 - (\gamma - 1)}{\gamma + 1}\right]^{\frac{-1}{\gamma-1}}$$

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The free-stream Mach number obtained from the wedge-rake survey was determined from oblique-shock theory. The ratio of wedge static pressure to wedge total pressure was plotted for a range of Mach numbers from 2.6 to 2.9 for a wedge included angle of 30°. The Mach number obtained from the right and left static- to total-pressure ratios was averaged to give the final Mach number.

The angle of flow deviation obtained from the wedge rakes was determined from oblique-shock theory by plotting the wedge static- to wedge total-pressure ratio against the average Mach number for constant lines of flow angle θ (ref. 6). Positive angles of flow were designated as the deviation to the left of the wedges and negative angles of flow, to the right of the wedges, looking downstream.

Operating

All data for this investigation were taken with no burning in the ram-jet engine and with supercritical operation of the inlet diffuser. The ranges of conditions over which the starting characteristics were investigated were:

(1) Nozzle-inlet total pressures from 1616 to 4080 pounds per square foot absolute

(2) Nozzle-inlet total temperatures from 66° to 528° F

(3) Humidities from 7 to 180 grains of water per pound of dry air

(4) Exhaust static pressures from 250 to 460 pounds per square foot absolute

The starting pressure-ratio investigation was conducted in the following manner: (1) A range of inlet temperatures and humidities was obtained by spraying various amounts of water into the inlet-air ducting upstream of the supersonic nozzle at several different air temperatures. (2) The facility pressure ratios for starting were established by changing the supersonic-nozzle-inlet pressure and maintaining a constant exhaust pressure for a given air flow.

The ranges of conditions over which the facility performance investigation was evaluated were:

(1) Nozzle-inlet total pressures from 1616 to 2900 pounds per square foot

(2) Nozzle-inlet total temperatures from 425° to 545° F

(3) Nozzle air flows from 100 to 180 pounds per second

(4) Humidities from 7 to 44 grains of water per pound of dry air 3205

(5) Over-all pressure ratios from 5.28 to 8.1

The facility performance investigation was conducted as follows: (1) The supply air to the facility was passed through the driers and combustion-air heaters. (2) Water was sprayed into the inlet-air ducting upstream of the supersonic-nozzle inlet at inlet-air total temperatures from about 90° to 300° F. (3) The inlet-air total pressures and exhaust static pressures were varied to give the desired pressure ratios at a particular air flow. (4) After the design flow had been established, the water was shut down and the air temperature permitted to rise to approximately 528° F.

PRESSURE-RATIO REQUIREMENTS OF FACILITY

Starting and Operating Techniques

Initial attempts to establish the design flow in the free-jet nozzle were unsuccessful, except on two or three occassions, even though over-all pressure ratios as high as 11 were attained. Free-jet nozzle wall static pressures, obtained during an unsuccessful attempt, are shown in figure 4(a) and verify that design flow had not been established. In general, the attempts to establish supersonic flow had been made with air heated to about 528° F and dried to a dew-point temperature from 5° to 45° F (7 to 44 grains of water per pound of dry air); this air temperature corresponds to the standard total temperature for a flight Mach number of 2.76 at altitudes above the tropopause. The humidity was selected to avoid a condensation shock in the supersonic nozzle at the particular air temperature in accordance with the results of reference 7.

Jet-diffuser wall static pressures, measured during an unsuccessful attempt to establish flow in the supersonic nozzle, are shown in figure 4(b) and indicate that critical flow existed in the throat of the jet diffuser. With these conditions existing, increased over-all pressure ratio would not be expected to cause establishment of the design flow

in the supersonic nozzle. In order to permit establishment of the flow, therefore, either the area of the jet-diffuser throat must be increased or some method must be used to lower the total-pressure losses upstream of the jet-diffuser throat.

An examination of the conditions existing during the successful starts revealed that the supersonic-nozzle inlet-air temperature was low (approximately 300° F) and that the moisture content of the air was probably appreciably higher than that allowable for condensation-free flow at this low temperature, according to reference 7. It was concluded that these conditions of low temperature and relatively high moisture content had been beneficial in starting the flow. Consequently, a water-spray system was installed in the upstream air duct ahead of the supersonic-nozzle inlet. Successful starts were then obtained by using moist, low-temperature air before attaining the desired inlet conditions.

The effects of moisture and temperature on starting and breakdown ratios were investigated and the results are shown in figure 5. It was found that the pressure ratios required to start the flow were substantially lowered by reducing the inlet temperature and increasing the humidity. The results shown in figure 5 indicate a pressure ratio of approximately 5 was sufficient to start the flow with an inlet-air temperature of 200° to 300° F and a moisture content in excess of 100 to 140 grains of water per pound of dry air, respectively. Although both temperature and moisture had an effect on the starting pressure ratio, the minimum operating pressure ratio was affected only by moisture content. It was possible to operate the facility at a pressure ratio of 4.55 with moisture contents above approximately 80 grains of water per pound of dry air; but when the moisture content of the air was reduced to approximately 7 grains, the minimum operating pressure ratio increased to about 6.0.

In consideration of the results shown in figure 5, the following procedure was used to establish the design flow in the facility: (1) The flow was started at a pressure ratio of about 5 by spraying water into the air downstream of the driers in the range of temperatures from approximately 90° to 200° F; (2) after the flow had started, the water spray was turned off, the pressure ratio raised to about 6, and the inlet air heated to approximately 528° F.

Effects of Condensation Shock

As indicated in reference 7, the moist inlet conditions, which permitted establishment of flow in the supersonic nozzle, were favorable to the formation of a condensation shock. Figure 6 shows that the supersonic-nozzle wall static pressures for established flow were higher with moist low-temperature air than with dry air at a temperature of 528° F and, therefore, that at the inlet conditions which permitted starting a condensation shock existed in the nozzle.

It was initially believed that the presence of a condensation shock might have lowered the Mach number of the air stream sufficiently to cause the large effect of moist low-temperature air on the starting pressure-ratio requirements. Figure 7 shows that the Mach number of the air stream determined from the pitot-tube rakes was only about 2 percent lower at inlet conditions for which a condensation shock was present than at inlet conditions for which the flow was free of a condensation shock. It was therefore concluded that the drop in the Mach number of the supersonic nozzle due to condensation shock was not the primary factor that resulted in the large effect of moist low-temperature air on the starting pressure-ratio requirements. 3205

Boundary-Layer Considerations

A possible explanation for the effectiveness of moist, low-temperature inlet air in reducing the starting pressure-ratio requirements may be found in the nozzle boundary-layer data. The effect of the low-temperature high-humidity air on the total-pressure profile of the boundary layer may be seen in figure 8. Two profiles are shown, one for normal operation of the nozzle with an inlet-air temperature of 528° F and a dew point of 5° F (7 grains of water per pound of dry air) and the other for conditions that permitted starting at an inlet-air temperature of 290° F and a dew point of 38° F (34 grains of water per pound of dry air). Both profiles are with the flow started. Undoubtedly a profile for unstarted flow would be different, but figure 8 can be used to show the trend in the boundary layer with the change in inlet temperature and humidity.

The average total pressure of the boundary layer was higher with the moist cool air than with the warm dry air used for normal operation, with the difference in pressures amounting to about 20 percent near the nozzle wall. The higher energy in the boundary layer with the moist cool air would, of course, tend to prevent flow separation from the walls of the nozzle; such separation probably existed during starting attempts with the warm dry air. Better flow attachment to the walls could improve the shock configuration in the nozzle and result in reduction of free-stream total-pressure losses. Energization of the boundary layer by the use of moist cool air, therefore, may have reduced the over-all total-pressure losses sufficiently to unchoke the throat of the jet diffuser and thereby permit the flow to become established in the nozzle.

Another reason for believing that boundary-layer configuration is involved in the starting problem is the fact that in this facility a large proportion of the flow passing underneath the supersonic inlet is boundary-layer air. A sharp pressure gradient from the flow around the wedge fairing could increase boundary-layer difficulties in this critical

area. Unpublished data from the circular facility of reference 3 (without this critical point) indicate that nozzle-inlet conditions had no appreciable effect on flow starting pressure-ratio requirements. Some lowering of the starting pressure ratio with condensation shock was noticed in the small-scale circular facility of reference 1; however, in the facility of reference 1, boundary layer was a greater proportion of the flow than in the larger facility of reference 3.

A more thorough investigation than was possible in this facility would be necessary to show the manner in which moist, low-temperature inlet air causes an increase of total pressure in the boundary layer. At least three possibilities exist: (1) The boundary layer would receive energy from water droplets (from the condensation shock) entering the boundary layer at near free-stream velocity; (2) changes in the boundary-layer temperature distribution due to the lower initial temperature and temperature loss through evaporation of the condensed water could influence the boundary-layer flow; (3) increased boundary-layer turbulence could result from the presence of either water droplets or decreased temperature and become a mechanism for entraining high-energy air in the boundary layer.

It is recognized that the effect of moist low-temperature air on the starting pressure-ratio requirements of a facility is dependent on the facility design and that the method undoubtedly could not be applied to all types of facility with success similar to that obtained in the investigation reported herein.

PERFORMANCE OF FACILITY

Mach Number Distribution and Flow Angle

Mach numbers obtained from the two types of instrumentation (wedge and pitot-tube rakes) are compared in figure 9. The Mach numbers obtained from the wedge rakes were lower than the Mach numbers obtained from the pitot-tube rakes, ranging from approximately 0.02 to 0.10 in Mach number difference. The Mach numbers obtained from the pitot-tube rakes, of course, require the assumption that all the total-pressure loss occurs across the normal shock ahead of the pitot tubes. Although the Mach numbers obtained from the wedge rakes involve no assumptions in theory, chances for instrumentation error are greater than for the pitot-tube instrumentation. It was felt, therefore, as shown in reference 8, that the pitot-tube instrumentation was the more accurate and these values were used.

Mach number distributions, which varied from -0.3 to 2.7 percent of the design Mach number of 2.755, are shown in figure 10 for various nozzle-inlet pressures and over-all facility pressure ratios. The data show that

there were no appreciable variations in Mach number due to (1) changes in the over-all facility pressure ratio from 5.3 to 8.1 at constant supersonic-nozzle-inlet temperature and pressure or (2) changes in the inlet pressure from 1980 to 2685 pounds per square inch absolute at constant inlet temperature and over-all pressure ratio. Thus as the inlet pressures are changed to vary the simulated altitude conditions, the supersonic-flow characteristics remain unaffected.

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The Mach number distribution across the nozzle was reasonably uniform, as indicated in figure 11(a), in which Mach number measurements of floor and ceiling rakes within the Mach cone at respective stations are superimposed. Figure 11(b) shows constant Mach number contours obtained from the measurements within the Mach cone as shown in figure 11(a). The unweighted average Mach number of the flow within the Mach cone was 2.76 with a variation of ±1.5 percent. The maximum Mach number was obtained near the floor at the center of the nozzle and gradually decreased along the radius of the nozzle. The area-weighted average Mach number of the flow within the portion of the Mach cone captured by the supersonic inlet was 2.765, as shown in figure 11(c).

The maximum deviation in flow angle as shown in figure 12 was $\pm 1.7^{\circ}$, which is considered a bit high but is probably caused by the inaccuracy of measurements obtained from the wedge rakes. A range of supersonic-nozzle-inlet pressures and facility pressure ratios had no appreciable effect on flow direction. In view of the relatively uniform Mach number distribution and low angles of flow deviation, the quality of flow is considered to be adequate to simulate the internal flow of the supersonic inlet, the inlet diffuser, and the 48-inch ram-jet engine at a Mach number of 2.76.

Pressure Distributions and Flow Observations

A comparison of measured wall static pressures with theoretical values along the length of the nozzle wall is shown in figure 13. The measured static pressures are in close agreement with the theoretical values.

Figures 14(a) and (b) show the boundary-layer profiles for the floor and ceiling rakes, respectively. The plots show that the profiles were not influenced by variations in inlet pressures or over-all pressure ratios. The measured thickness of the boundary layer on the floor was approximately 2 inches as compared with the calculated thickness of 1.67 inches. The measured thickness of the ceiling boundary layer was approximately 2.25 inches as compared with a calculated thickness of 1.83 inches.

Shadowgraph pictures for over-all pressure ratios of 6, 7, and 8 are shown in figure 15. The location at which the shadowgraph pictures were

taken is shown in the sketch on the same figure. Because the jet-chamber pressure was always higher than the nozzle-exit pressure, a shock wave originated at the exit of the supersonic nozzle. The exit shock wave fell downstream of the supersonic inlet, thus the internal flow to the ram-jet engine was not disturbed.

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The performance of the jet diffuser at two facility pressure ratios can be seen in figure 16. Pressure distributions along the jet-diffuser outer contour are shown for established flow at pressure ratios of 7.98 and 5.28. At the higher pressure ratio, the minimum effective area of the jet diffuser appeared to be located at station 15. This location could be due to possible separation of the boundary layer and then reattachment, and could account for the deceleration and acceleration of the flow which terminates in a shock as indicated by the steep pressure rise beginning at station 67 and ending approximately at station 126. At the pressure ratio of 5.28, which is close to the breakdown value, the shock was moved upstream and appears to be very close to the geometric throat.

CONCLUDING REMARKS

The design flow (Mach number of 2.755) could not be established in the free-jet facility with dry inlet air at a temperature of 528° F and over-all pressure ratios up to 11. The desired flow, however, was started at an over-all pressure ratio as low as 5 by using low-temperature inlet air with high moisture content. Energization of the boundary layer is believed responsible for this change. It was necessary to maintain an over-all pressure ratio of about 6 when the facility was operated at an inlet-air temperature of 528° F with a dew-point temperature from 5° to 45° F (7 to 44 grains of water per pound of dry air).

The investigation showed the free-jet flow to be sufficiently uniform in velocity and flow angle to satisfactorily simulate the internal flow of the supersonic inlet, the inlet diffuser, and the 48-inch ram-jet engine. The average-weighted Mach number of the inlet capture area was 2.765. The Mach number varied from -0.3 to 2.7 percent of the design Mach number of 2.755. The maximum angle of flow deviation was ±1.7°.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 22, 1954

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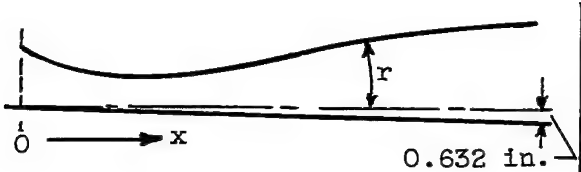
TABLE I. - NOZZLE COORDINATES

x, in.	r, in.	x, in.	r, in.	x, in.	r, in.
0	27.379	72.000	17.848	116.000	23.691
6.000	26.039	72.500	17.850	120.000	24.370
12.000	24.781	73.000	17.853	124.000	25.030
18.000	23.592	73.500	17.857	128.000	25.674
24.000	22.519	74.000	17.863	131.500	26.220
30.000	21.518	74.500	17.870	134.000	26.597
35.500	20.677	75.000	17.879	138.000	27.173
36.000	20.615	76.000	17.905	142.000	27.725
38.000	20.360	77.000	17.939	146.000	28.254
40.000	20.098	78.000	17.982	150.000	28.760
42.000	19.851	79.000	18.035	154.000	29.212
44.000	19.611	80.000	18.098	158.000	29.603
46.000	19.395	81.000	18.172	162.000	29.965
48.000	19.184	82.000	18.255	166.000	30.306
50.000	18.996	83.000	18.346	170.000	30.627
52.000	18.813	83.500	18.394	174.000	30.929
54.000	18.635	84.000	18.443	178.000	31.213
56.000	18.463	86.000	18.666	181.500	31.448
58.000	18.313	88.000	18.912	184.000	31.608
60.000	18.185	90.000	19.180	188.000	31.844
62.000	18.074	92.000	19.468	192.000	32.064
64.000	17.984	94.000	19.776	196.000	32.268
66.000	17.917	96.000	20.101	200.000	32.452
67.000	17.891	98.000	20.443	204.000	32.602
68.000	17.873	100.000	20.801	208.000	32.730
69.000	17.858	102.000	21.171	212.000	32.837
69.500	17.853	104.000	21.543	216.000	32.927
70.000	17.850	106.000	21.913	220.000	33.009
70.500	17.848	108.000	22.278	224.000	33.084
71.000	17.847	110.000	22.639	228.000	33.145
71.500	17.847	112.000	22.995	230.123	33.169



Floor	
x, in.	Distance below center line, in.
0	0
71.000	.058
83.500	.068
230.123	.632

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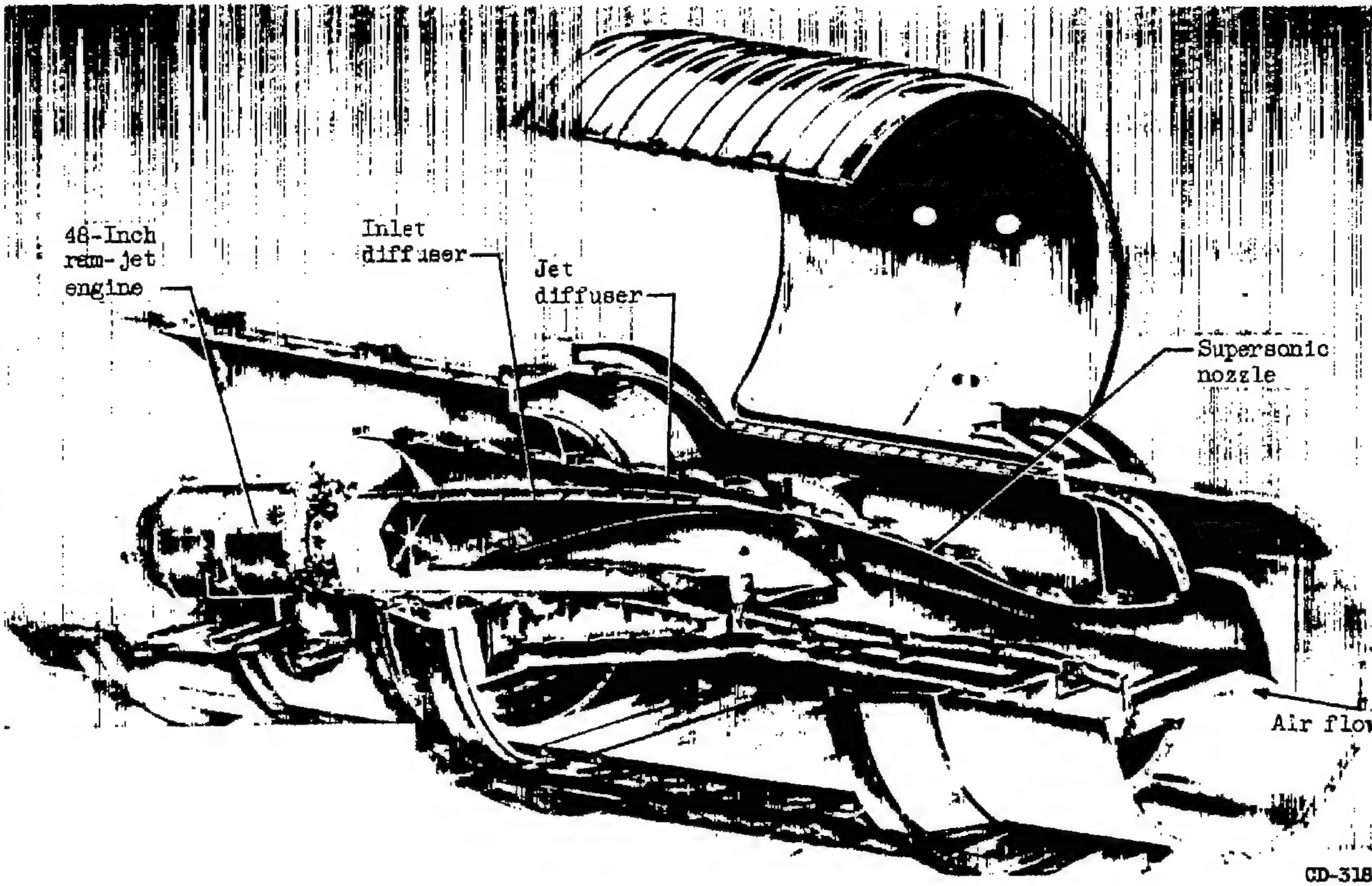

Figure 1. - Free-jet installation.

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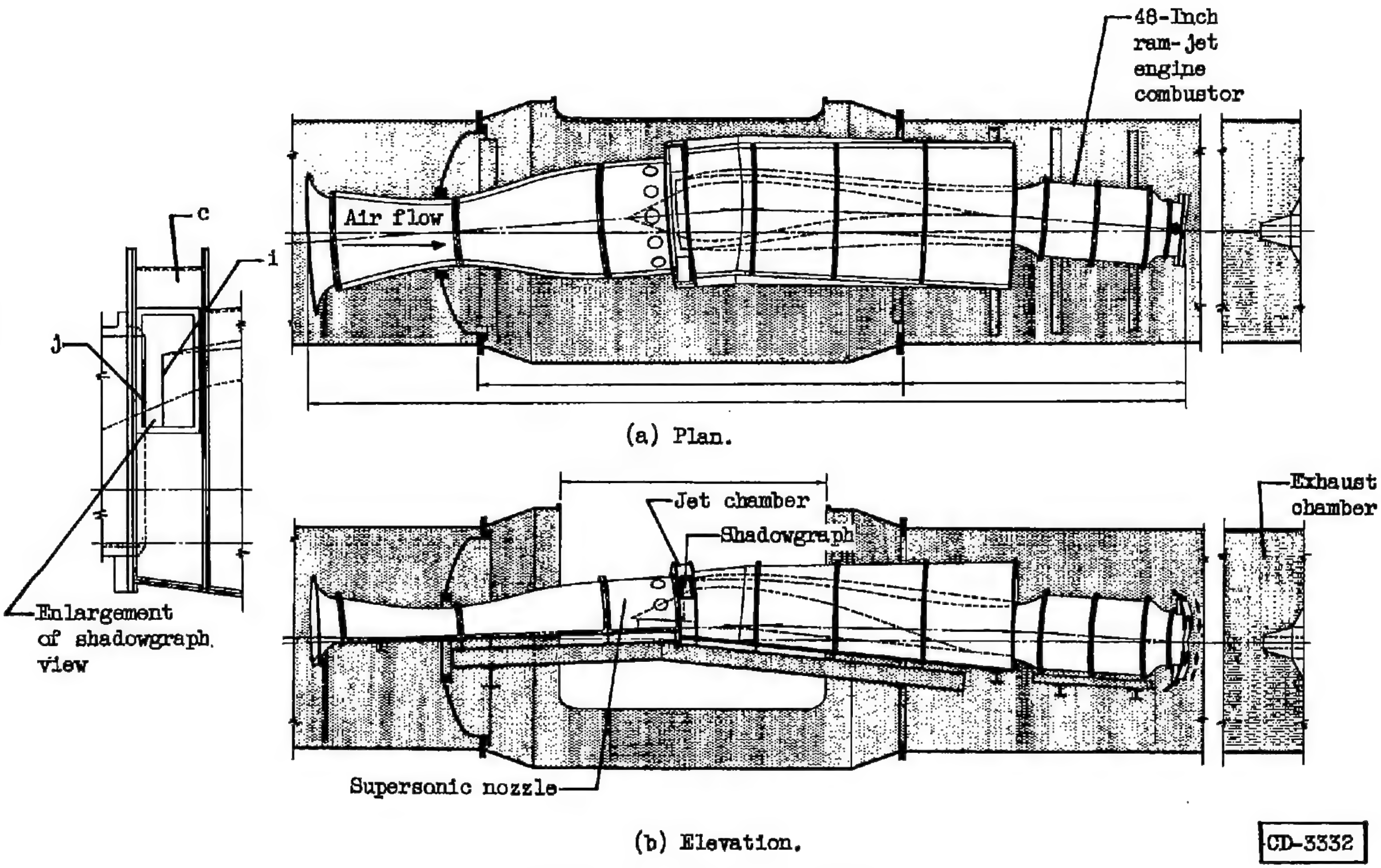
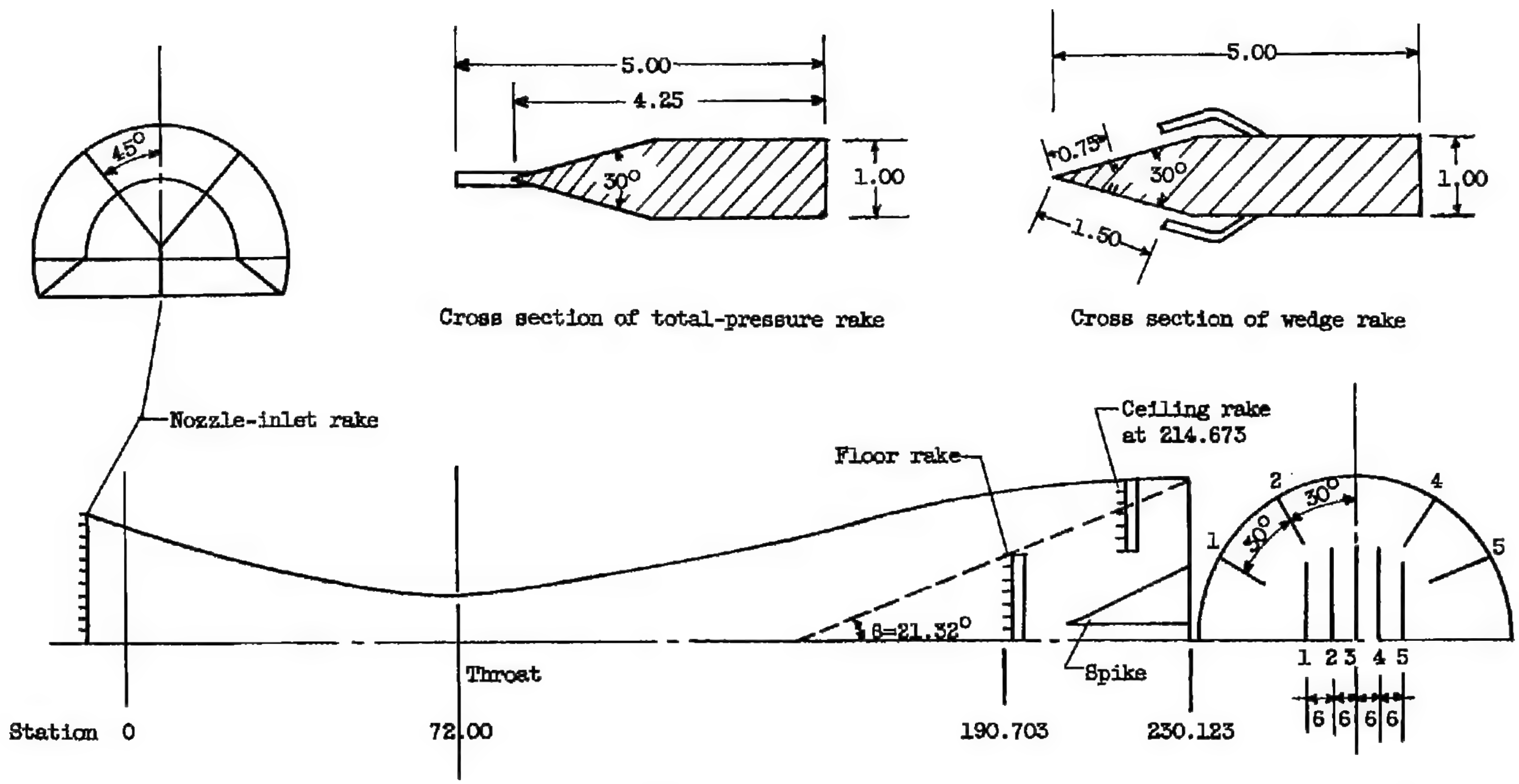


(a) Plan.

(b) Elevation.

Figure 2. - Free-jet facility.

CONFIDENTIAL



Cross section of total-pressure rake

Cross section of wedge rake

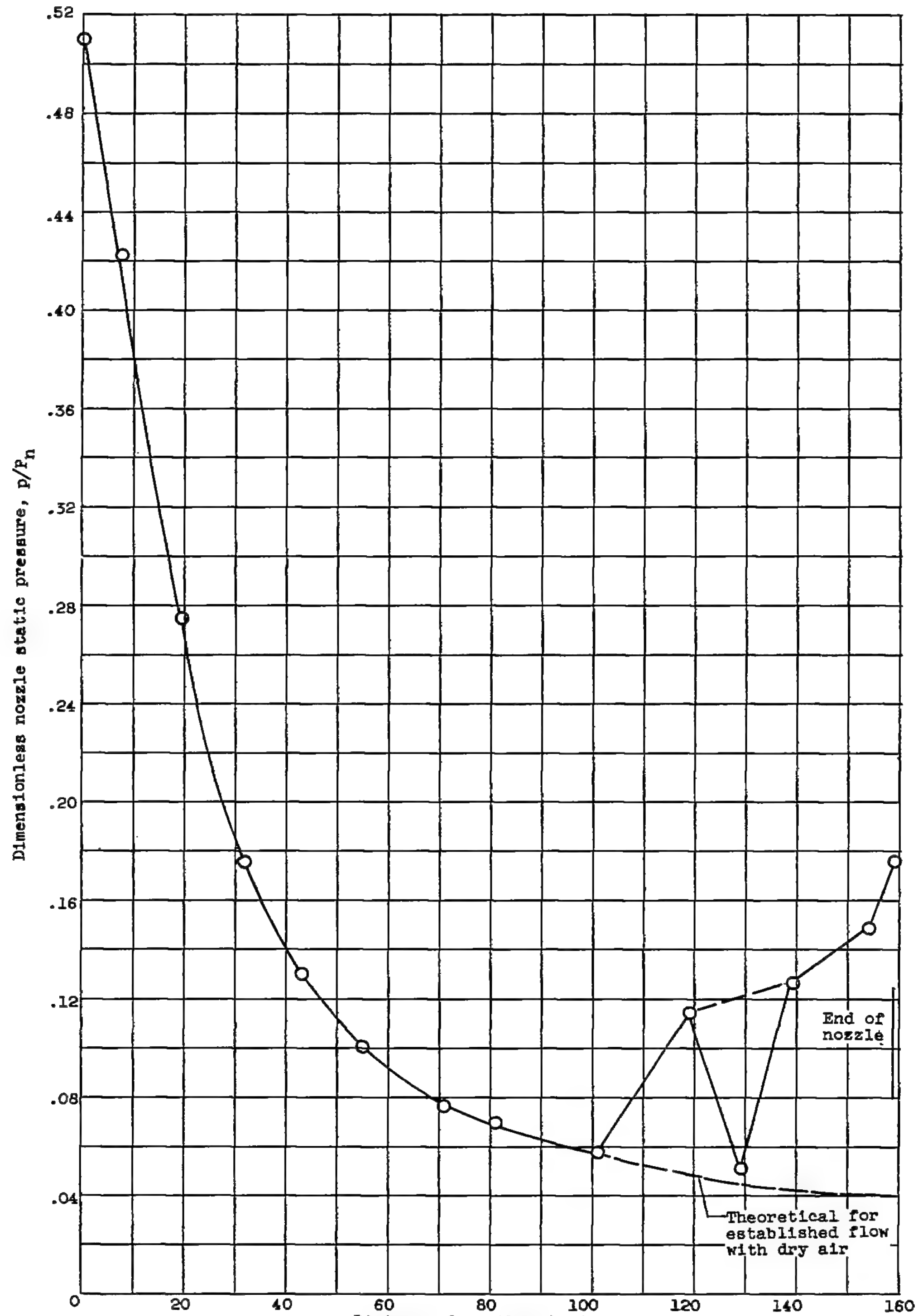
Longitudinal section

Cross section of nozzle

Figure 3. - Rake details and locations. (All dimensions in inches.)

3205

CP-3 back



(a) Nozzle wall static pressure.

Figure 4. - Static-pressure distribution for unstarted flow. Nozzle-inlet temperature, 452° F; dew point, 36° F; air flow, 191 pounds per second; pressure ratio, 9.76; nozzle-inlet pressure, 3100 pounds per square foot absolute.

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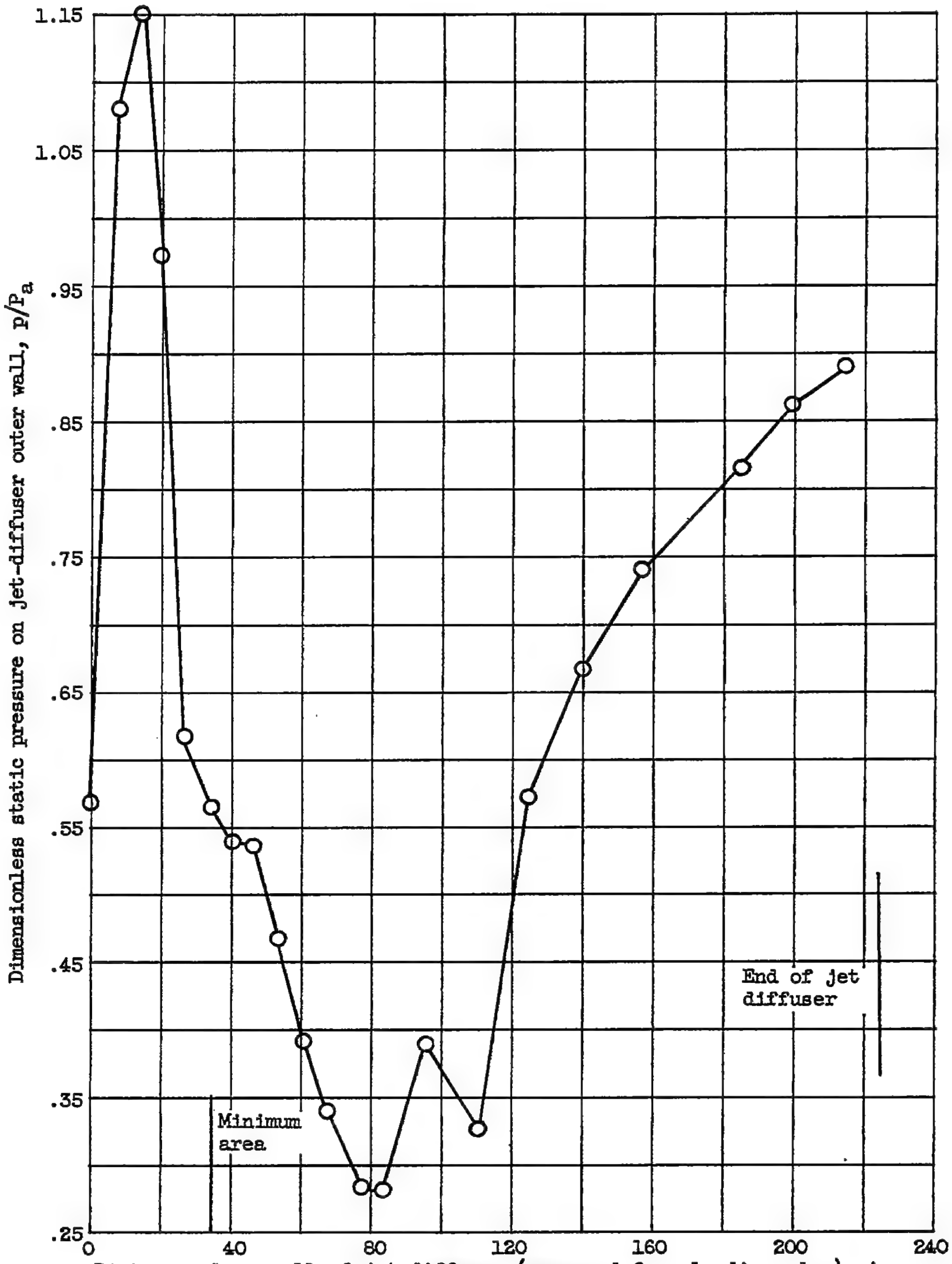


(b) Jet-diffuser static pressure.

Figure 4. - Concluded. Static-pressure distribution for unstarted flow. Nozzle-inlet temperature, 452° F; dew point, 36° F; air flow, 191 pounds per second; pressure ratio, 9.76; nozzle-inlet pressure, 3100 pounds per square foot absolute.

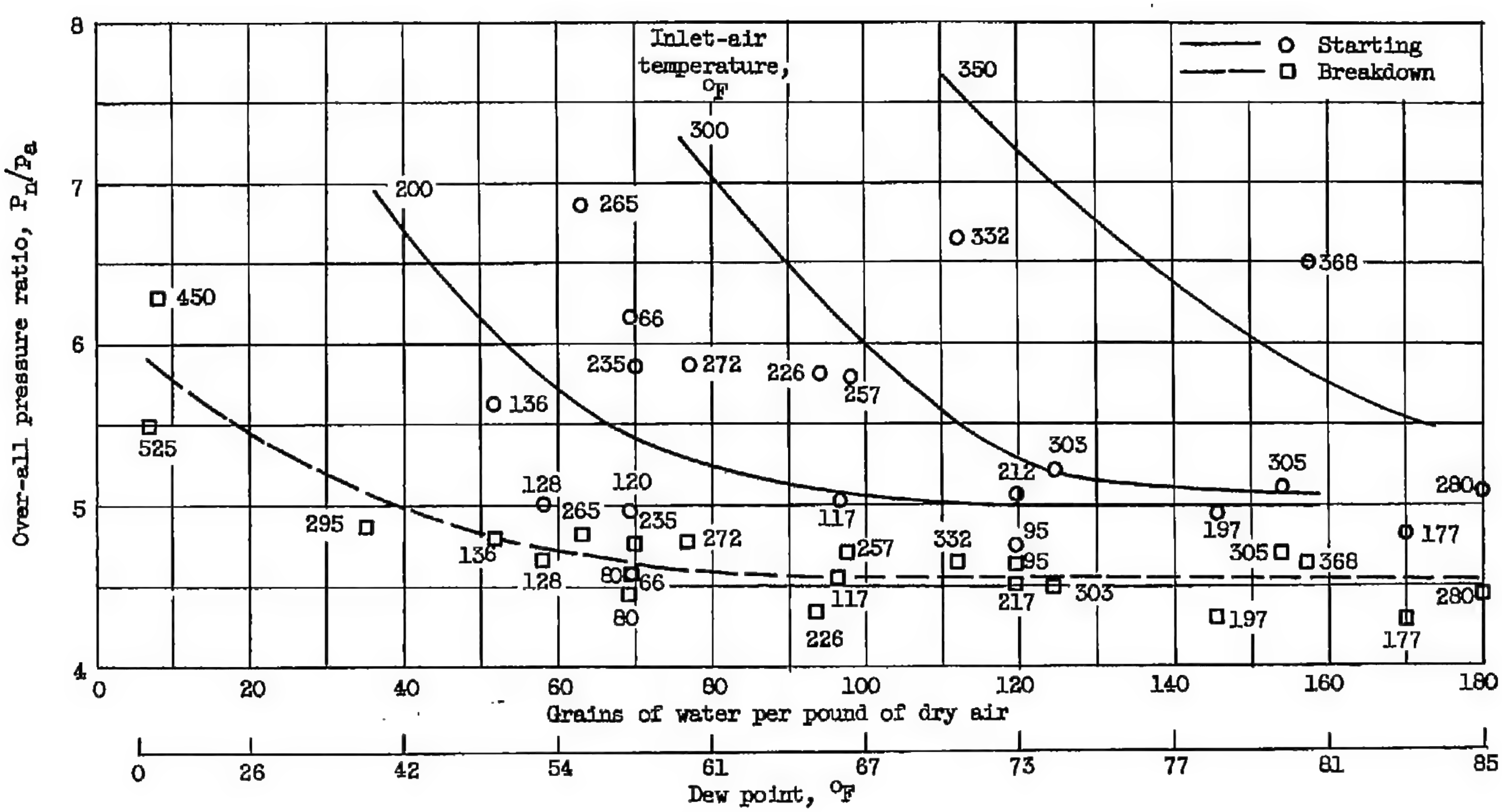


Figure 5. - Starting and breakdown pressure-ratio requirements for various nozzle inlet-air temperatures and moisture content.

3205

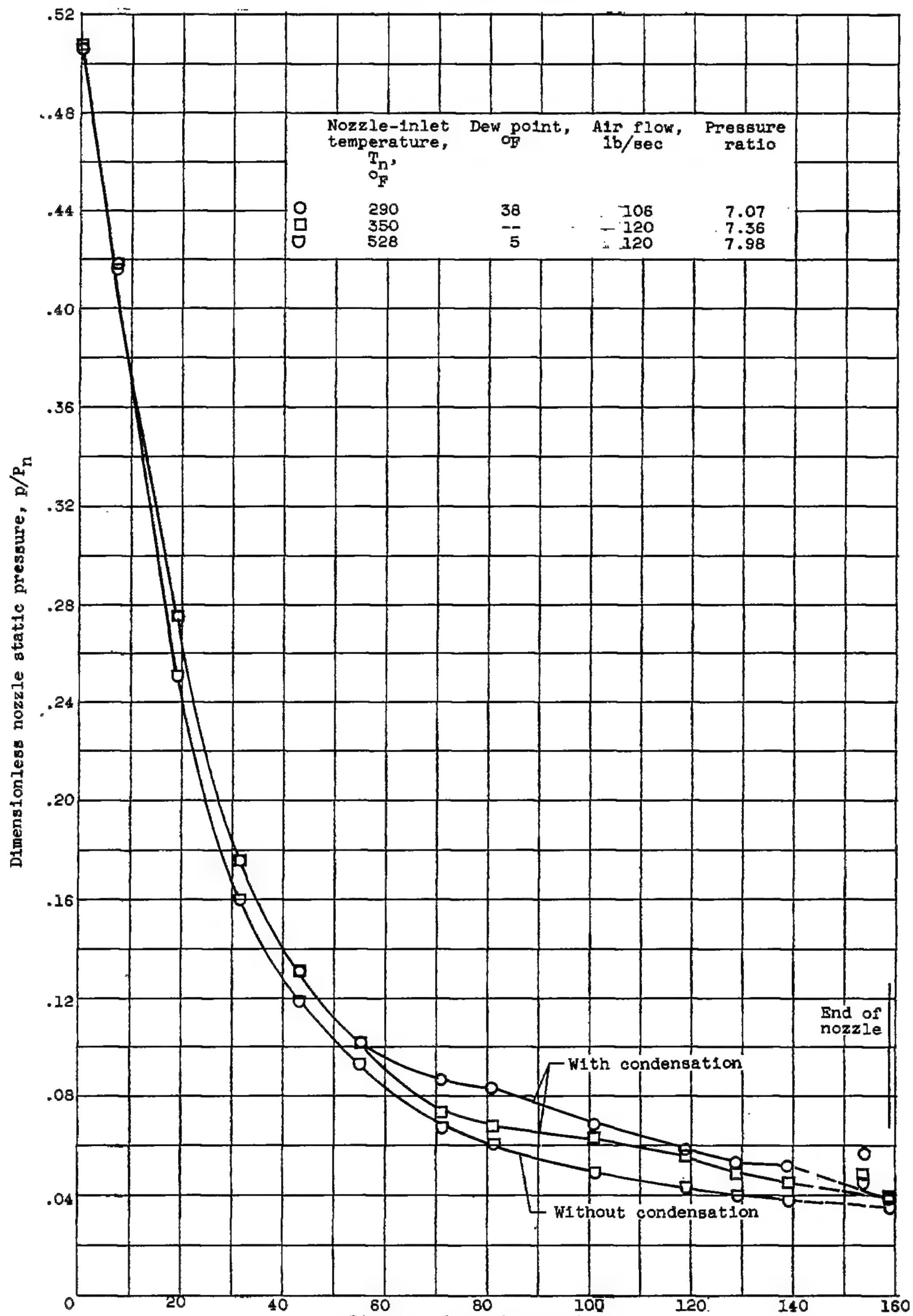
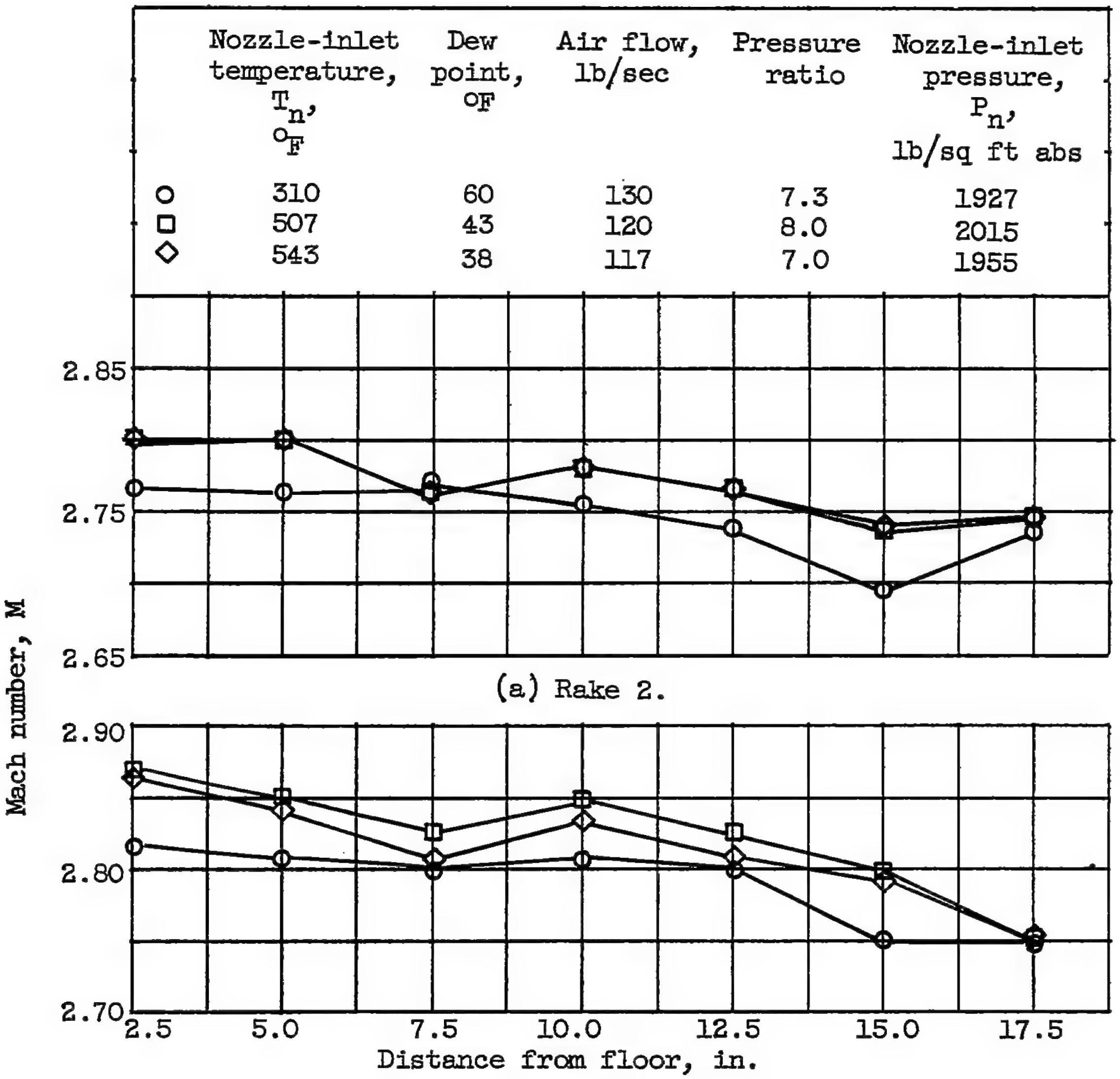


Figure 6. - Comparison of nozzle wall static pressures with and without condensation shock.

3205



(a) Rake 2.

(b) Rake 4.

Figure 7. - Mach number decrease due to effects of condensation shock.

3205

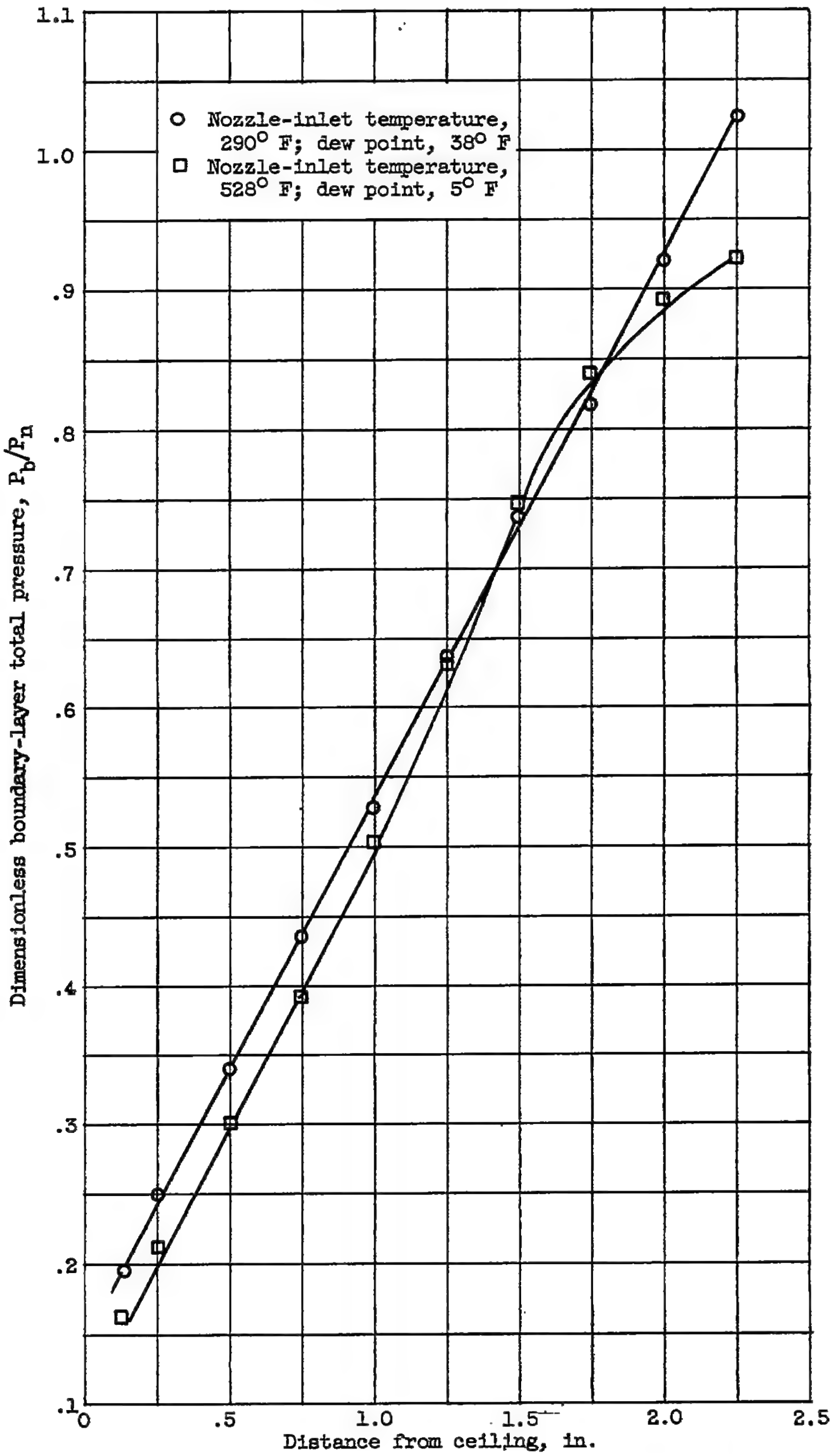
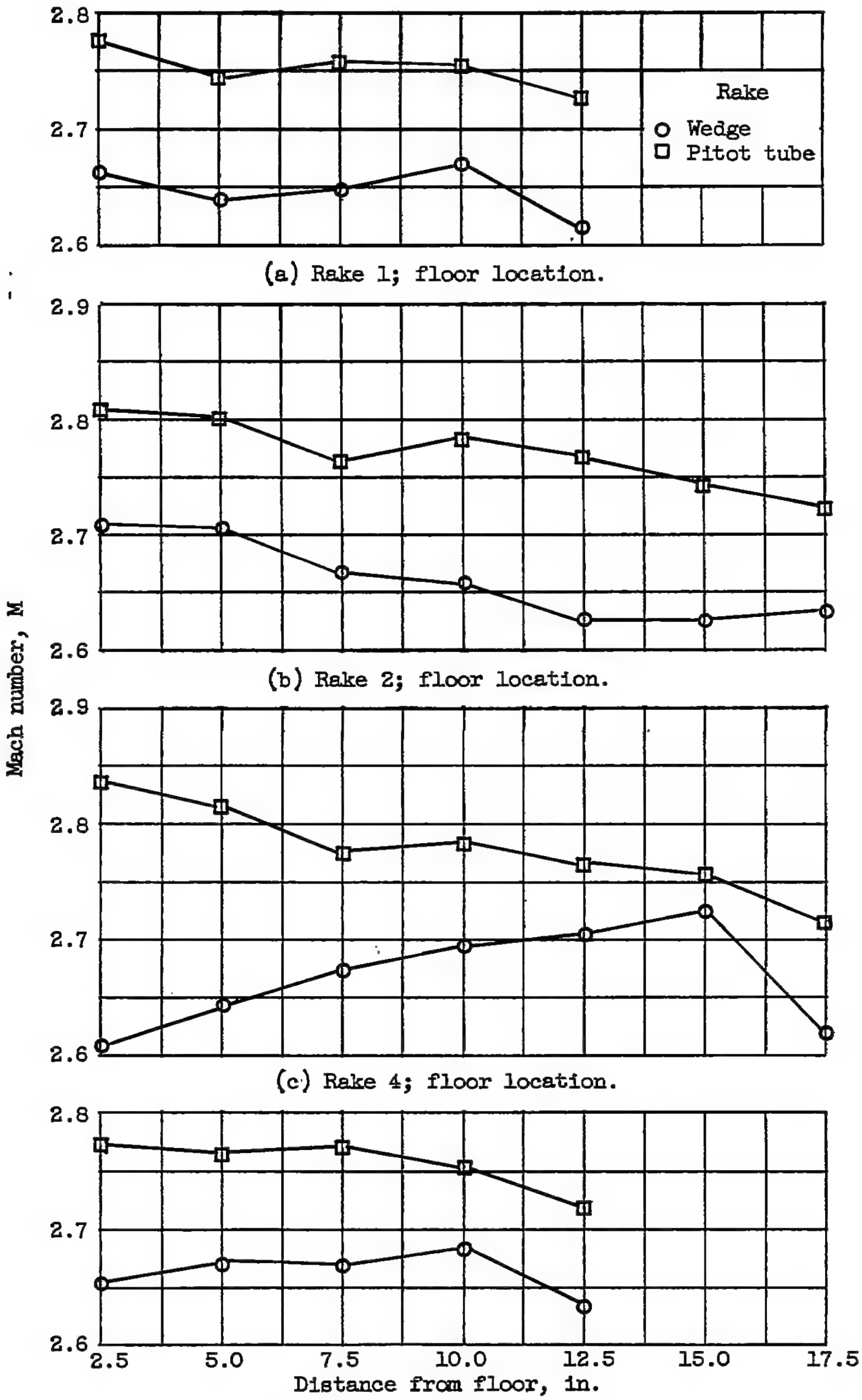


Figure 8. - Influence of moist air on boundary-layer total pressure.



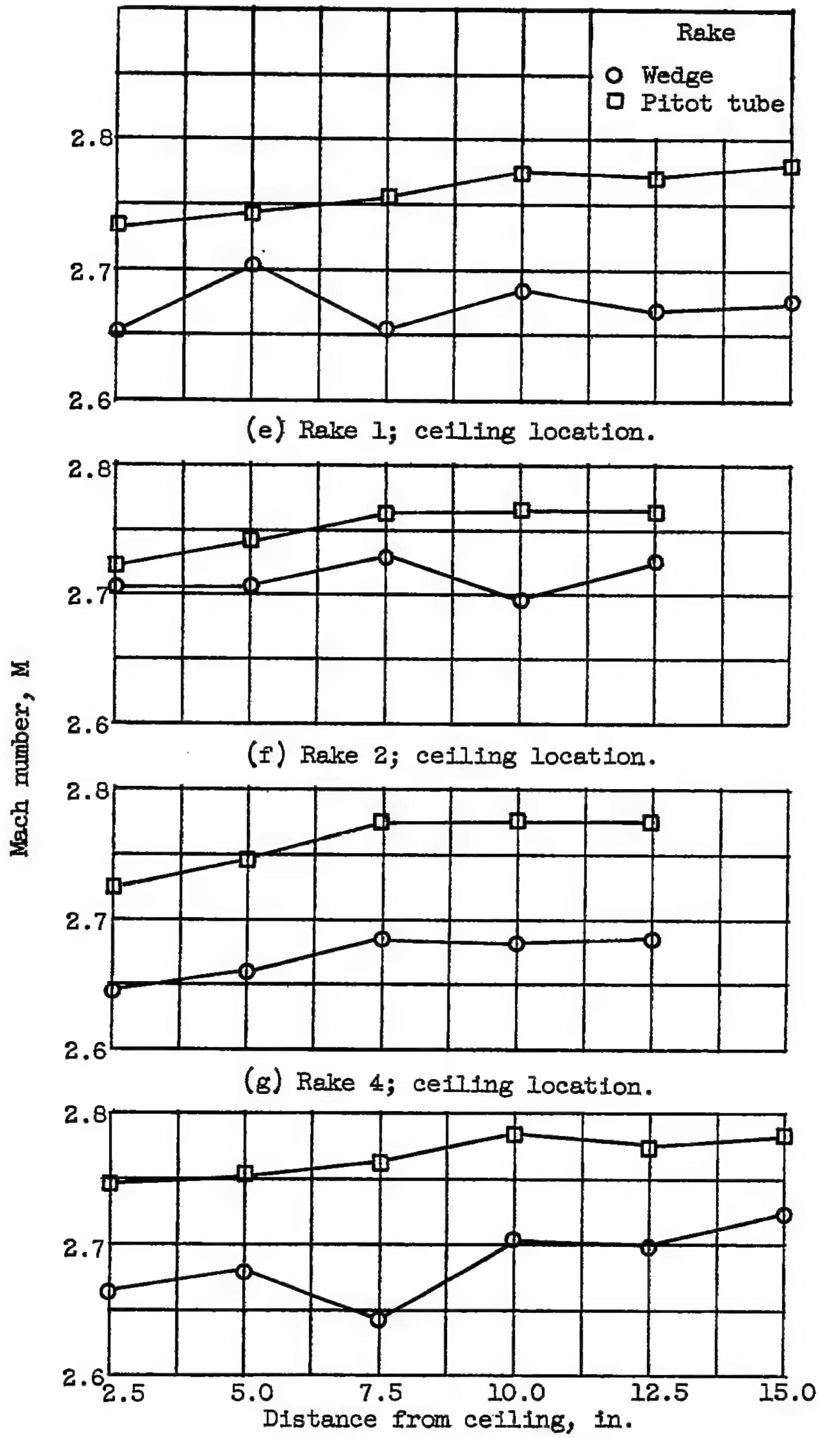
(a) Rake 1; floor location.

(b) Rake 2; floor location.

(c) Rake 4; floor location.

(d) Rake 5; floor location.

Figure 9. - Supersonic-nozzle Mach number comparisons with pitot-tube and wedge rakes.



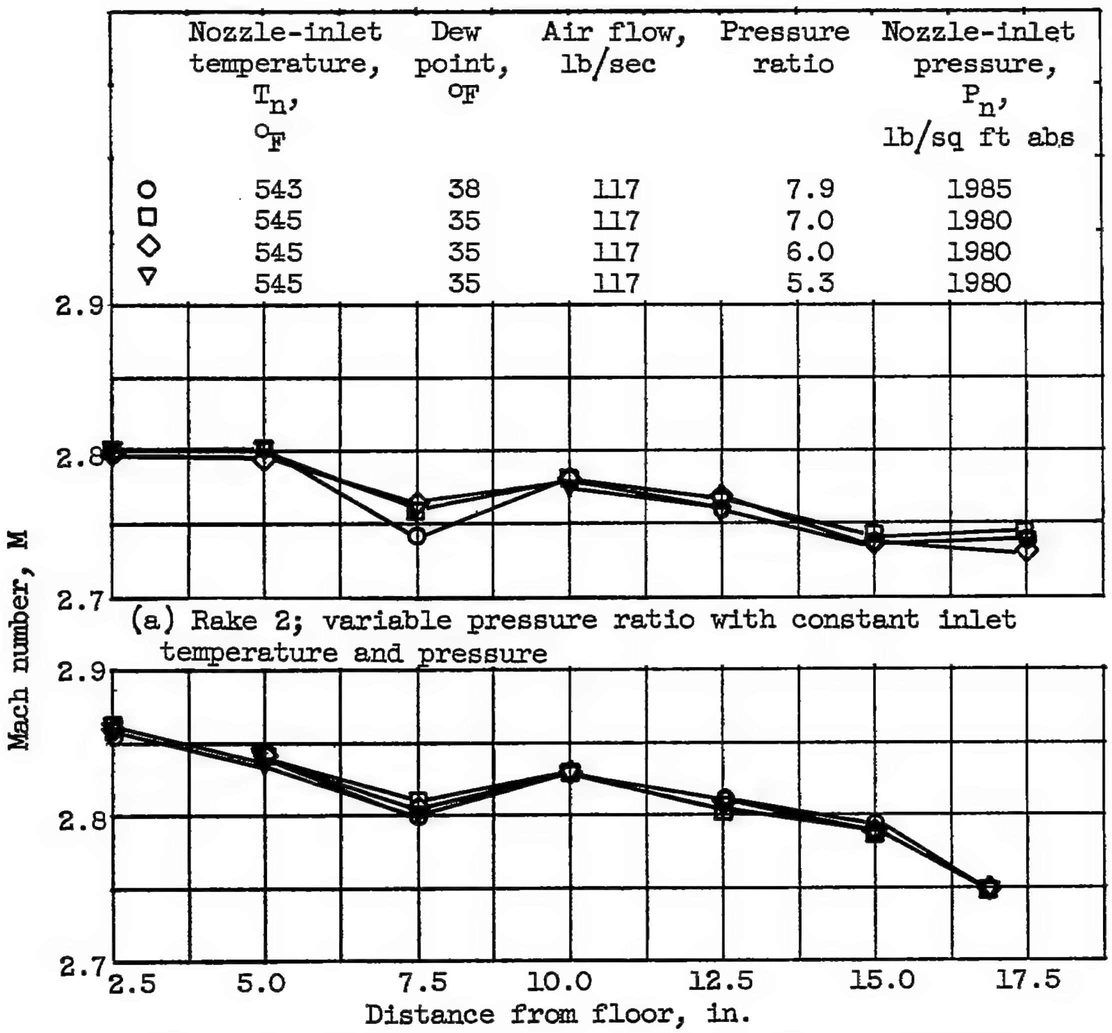
(e) Rake 1; ceiling location.

(f) Rake 2; ceiling location.

(g) Rake 4; ceiling location.

(h) Rake 5; ceiling location.

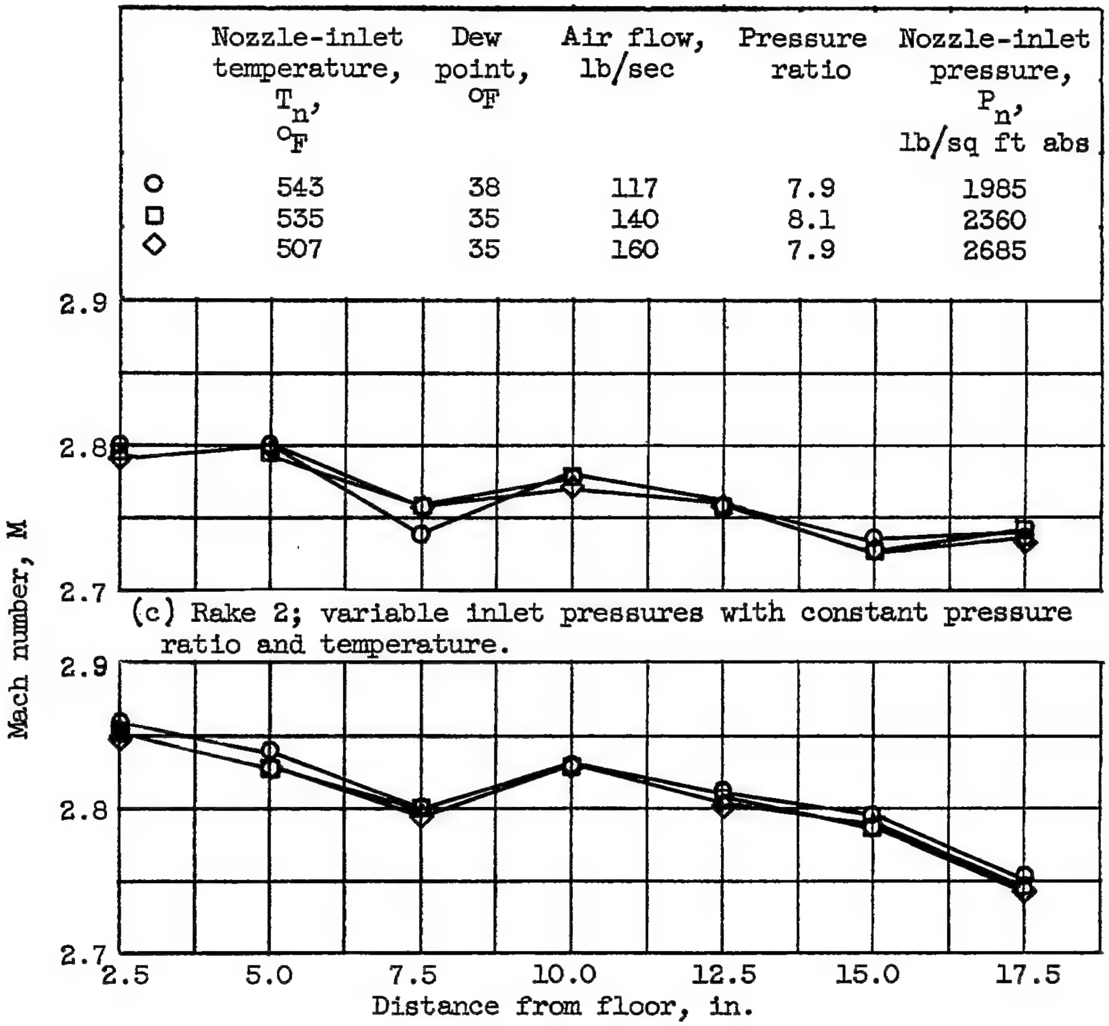
Figure 9. - Continued. Supersonic-nozzle Mach number comparisons with pitot-tube and wedge rakes.



(a) Rake 2; variable pressure ratio with constant inlet temperature and pressure

(b) Rake 4; variable pressure ratio with constant inlet temperature and pressure.

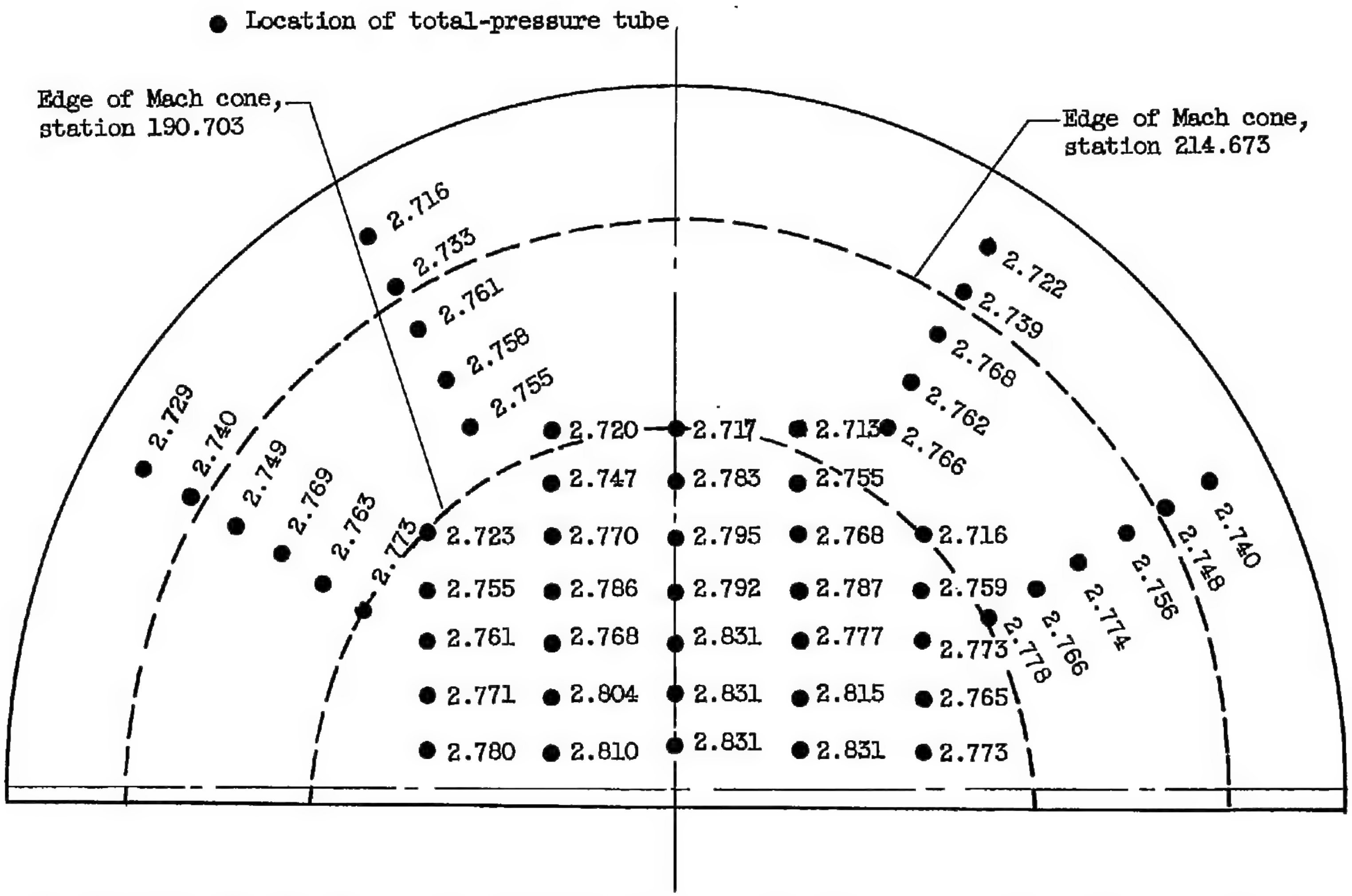
Figure 10. - Mach number distribution from floor rakes.



(c) Rake 2; variable inlet pressures with constant pressure ratio and temperature.

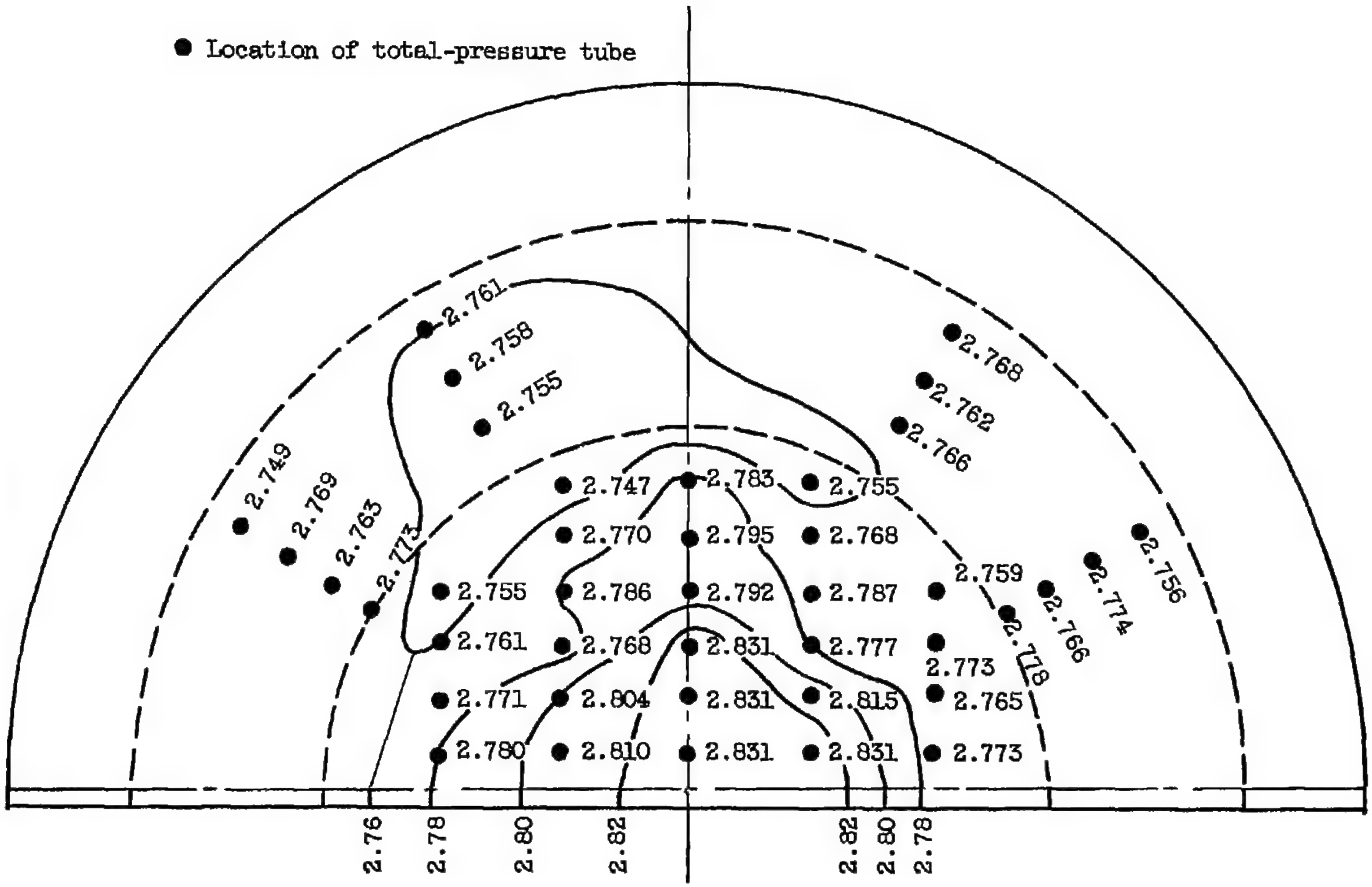
(d) Rake 4; variable inlet pressures with constant pressure ratio and temperature.

Figure 10. - Concluded. Mach number distribution from floor rakes.



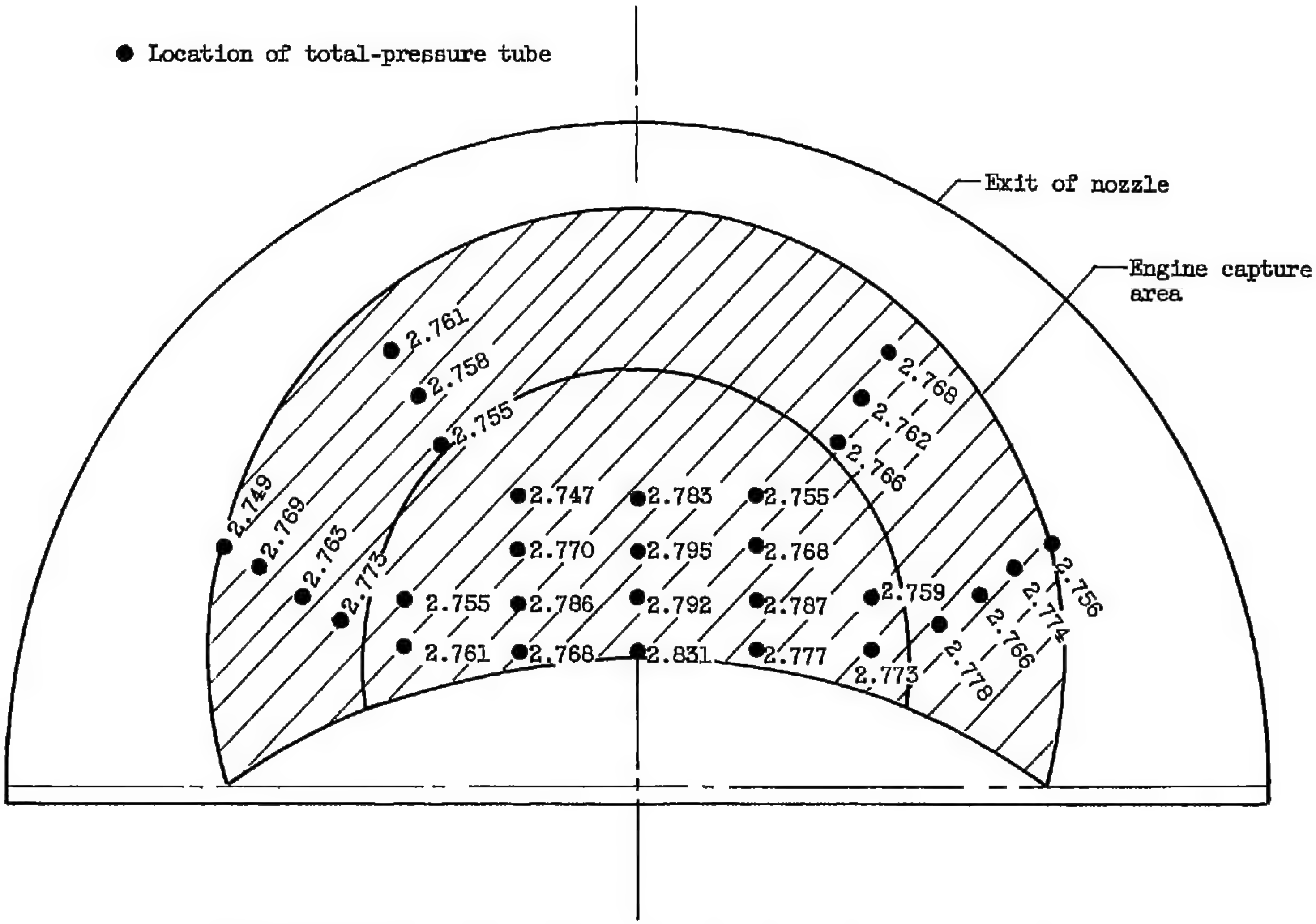
(a) Stations 190.703 (floor total-pressure rakes) and 214.673 (ceiling total-pressure rakes).

Figure 11. - Supersonic-nozzle Mach number distributions.



(b) Contours.

Figure 11. - Continued. Supersonic-nozzle Mach number distributions.



(c) Area-weighted average Mach number of inlet capture area, 2.765.

Figure 11. - Concluded. Supersonic-nozzle Mach number distributions.

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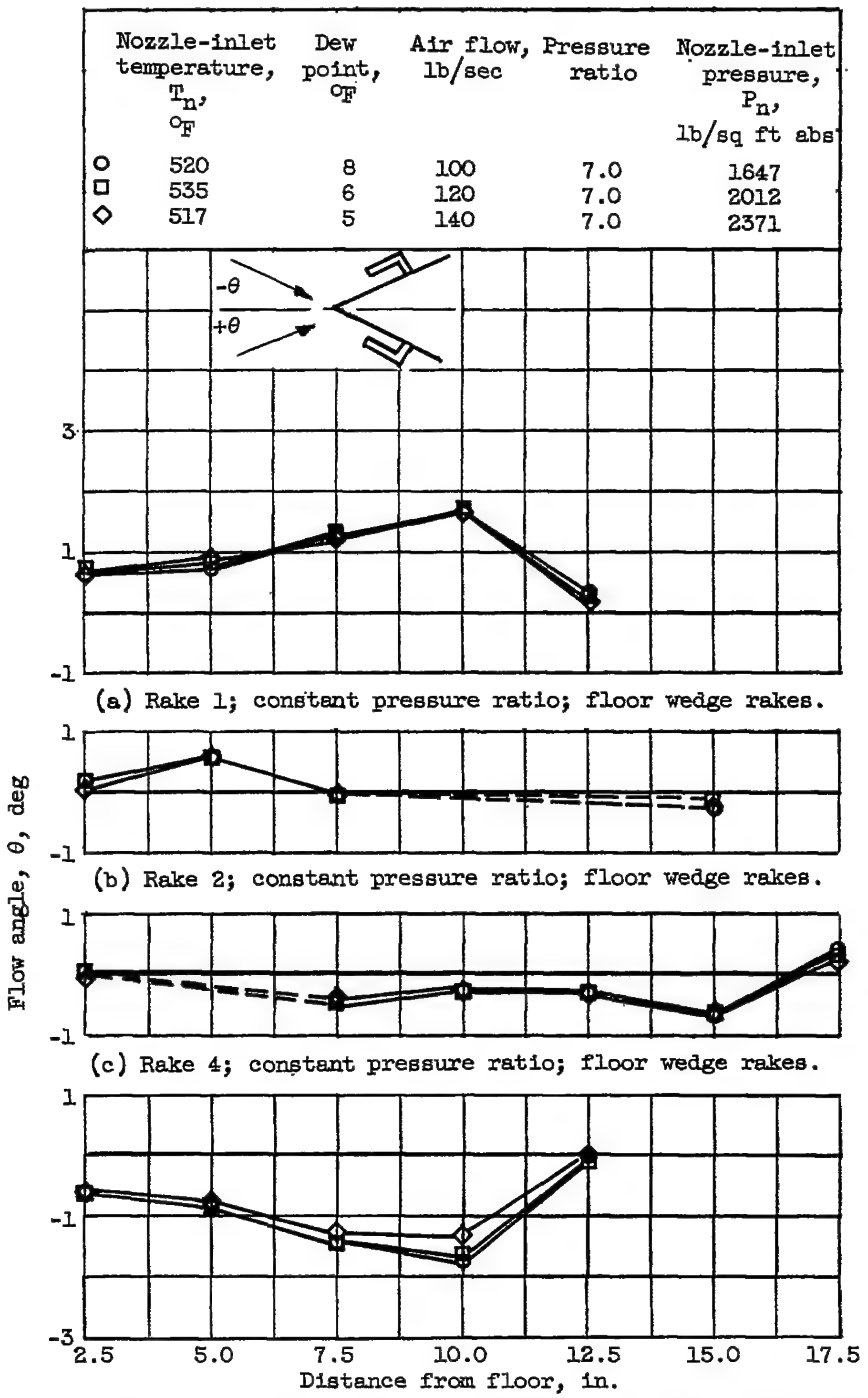

(d) Rake 5; constant pressure ratio; floor wedge rakes.

Figure 12. - Comparison of flow-angle deviation with variable air flows.

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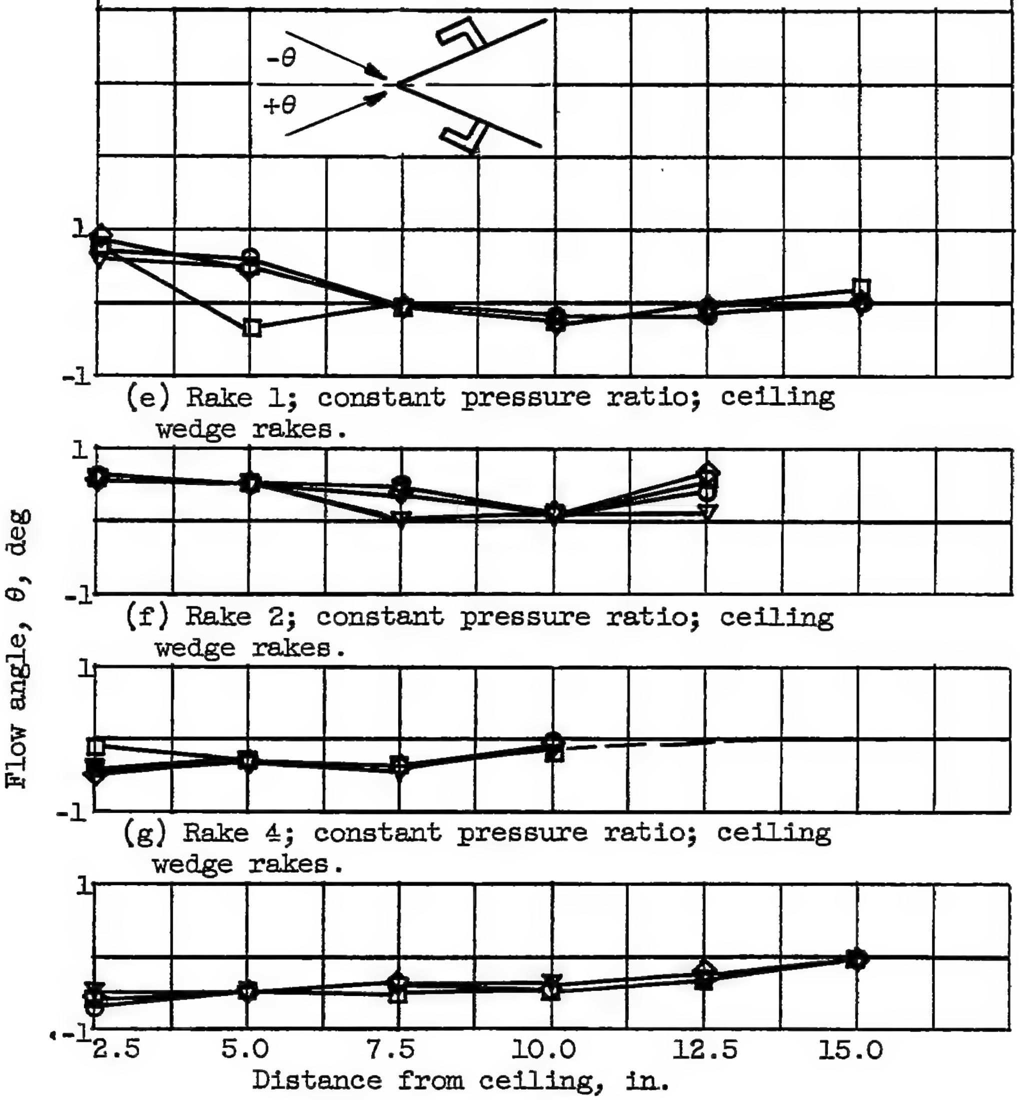
	Nozzle-inlet temperature, T_n, °F	Dew point, °F	Air flow, lb/sec	Pressure ratio	Nozzle-inlet pressure, P_n, lb/sq ft abs
○	530	11	100	6.91	1670
□	530	4	120	7.03	2019
◇	512	6	140	7.3	2417
▽	477	6	160	7.5	2715



(e) Rake 1; constant pressure ratio; ceiling wedge rakes.

(f) Rake 2; constant pressure ratio; ceiling wedge rakes.

(g) Rake 4; constant pressure ratio; ceiling wedge rakes.

(h) Rake 5; constant pressure ratio; ceiling wedge rakes.

Figure 12. - Concluded. Comparison of flow-angle deviation with variable air flows.

[redacted]

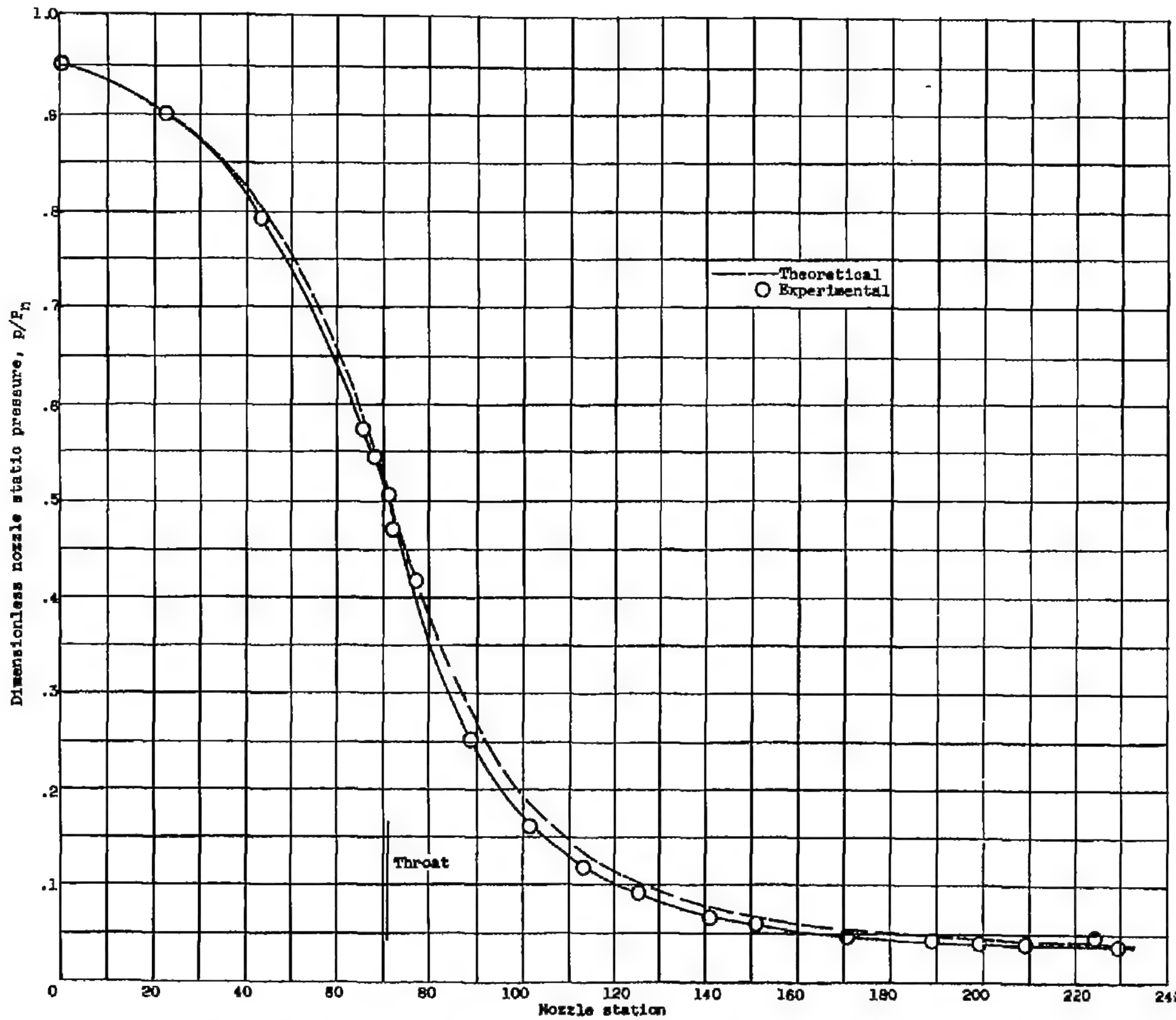
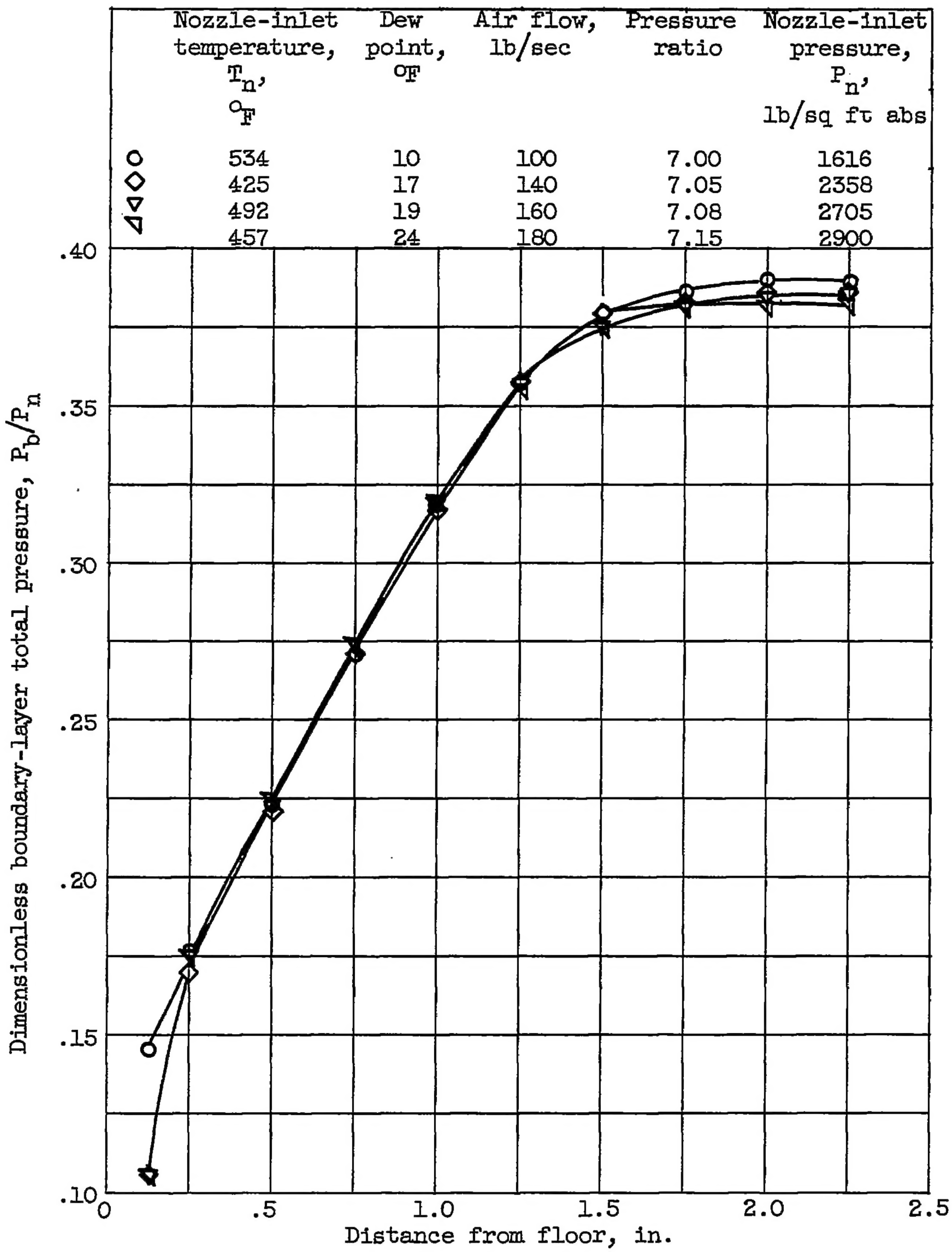


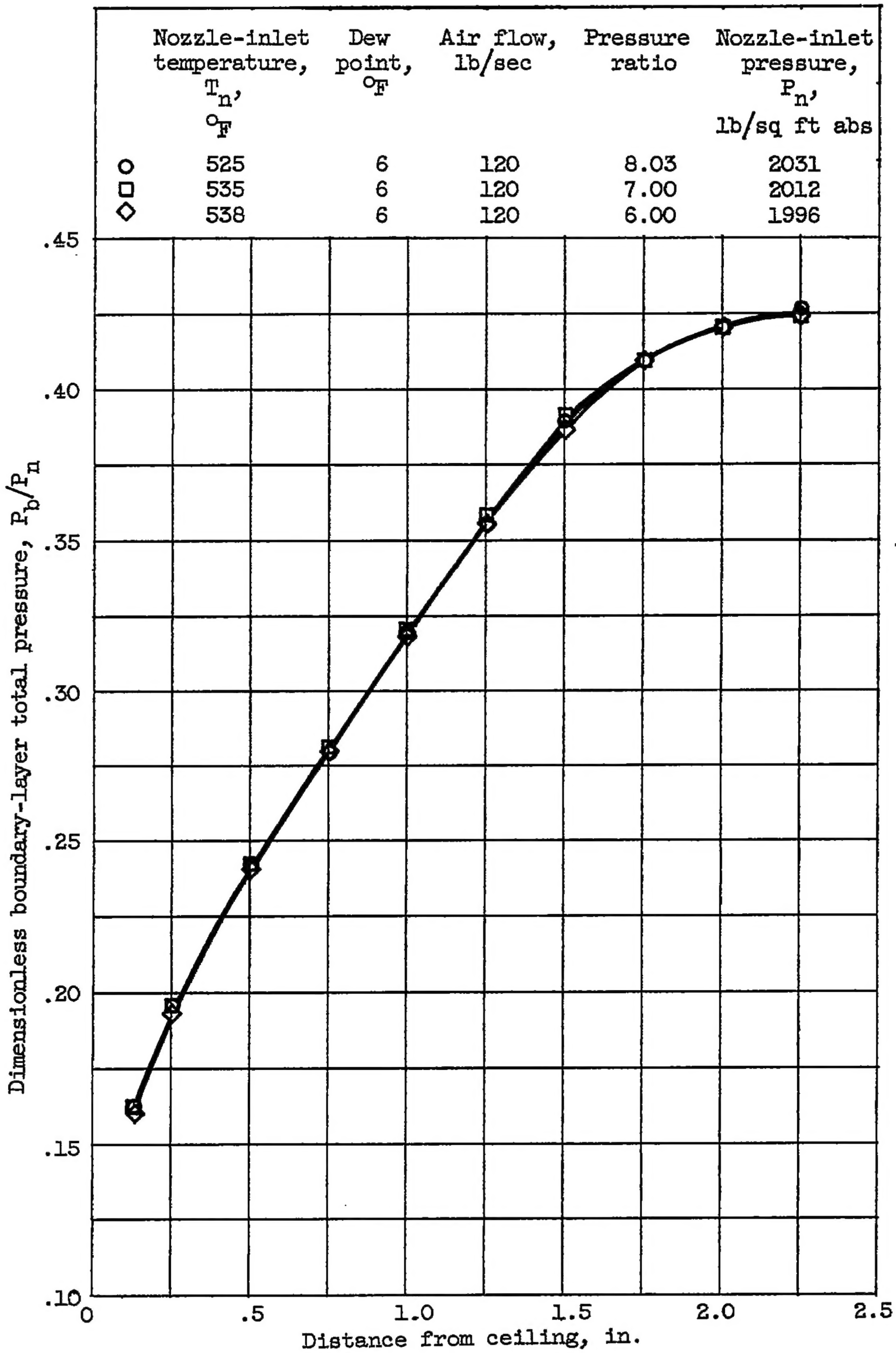
Figure 13. - Comparison of experimental and theoretical nozzle wall static pressures.

[redacted]



(a) Floor; variable air flow; constant pressure ratio.

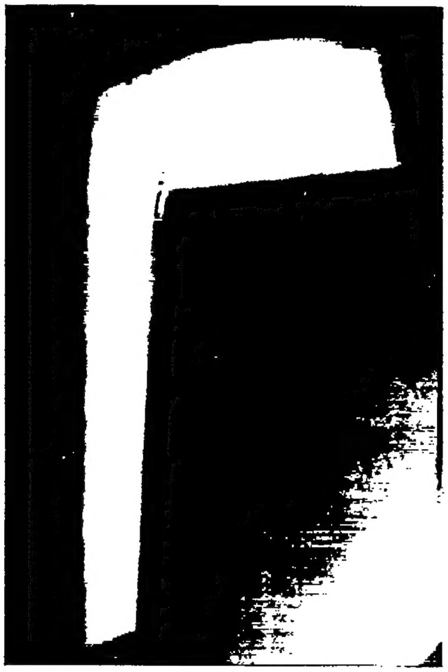
Figure 14. - Boundary-layer profiles.



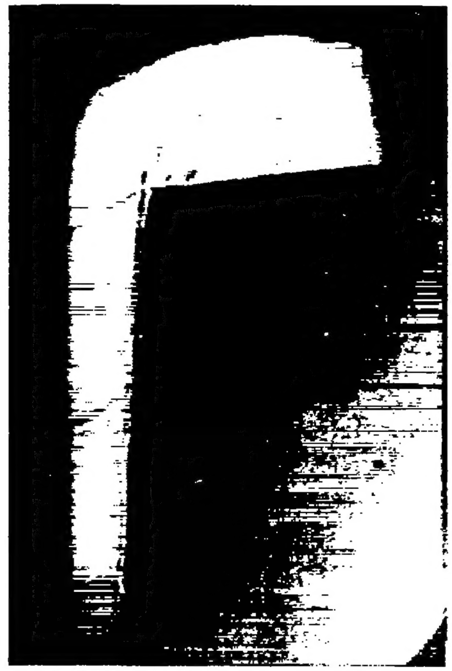
(b) Ceiling; constant air flow; variable pressure ratio.

Figure 14. - Concluded. Boundary-layer profiles.

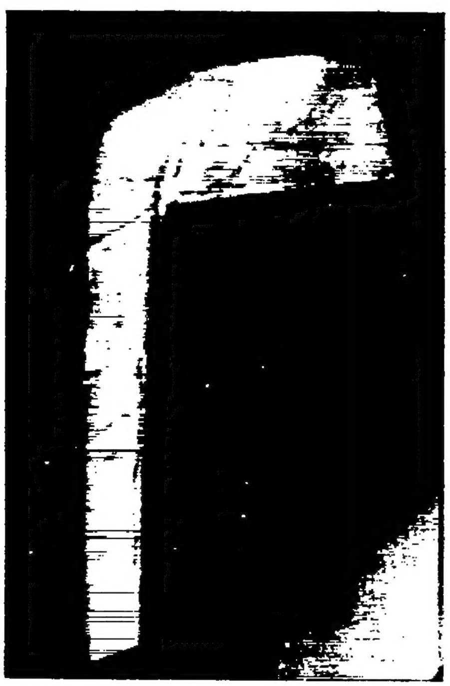
3205



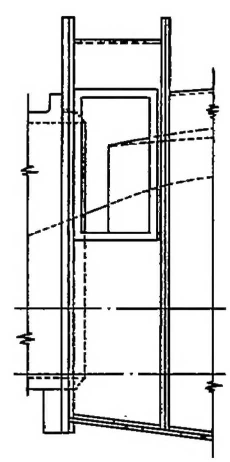
(a) Pressure ratio, 6.



(b) Pressure ratio, 7.



(c) Pressure ratio, 8.



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Location

Figure 15. - Shadowgraph pictures taken at supersonic inlet for pressure ratios of 6, 7, and 8.

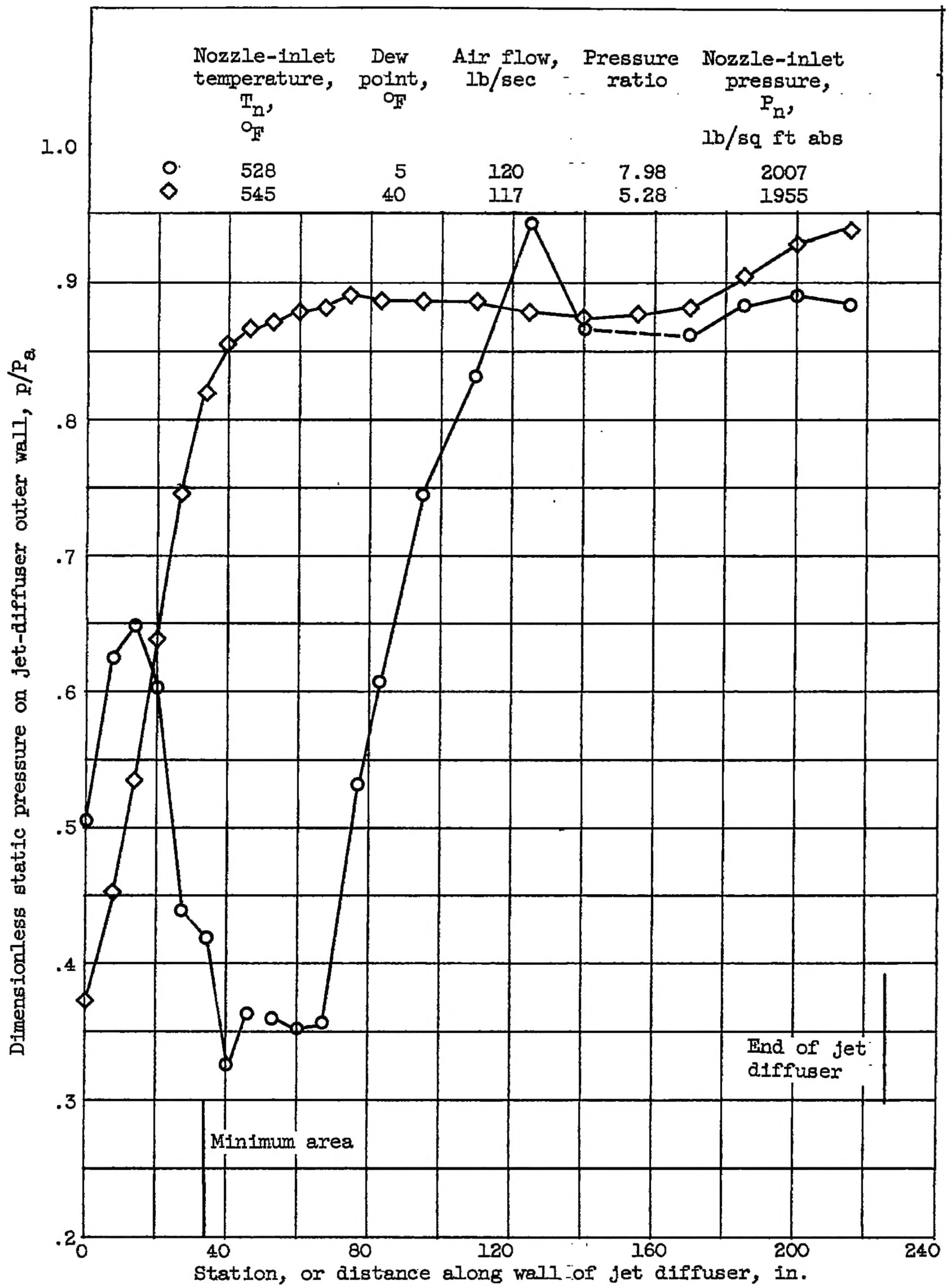

Figure 16. - Pressure distributions along jet diffuser for established flow.